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David W. Taylor Naval Ship Research and Development Center

SOUND POWER MEASUREMENTS IN AIR IN THE
NEAR FIELD OF SOUND SOURCES USING THE
SOUND INTENSITY METHOD

by
John Roger Polak

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AD-A183348

REPORT DOCUMENTATION PAGE
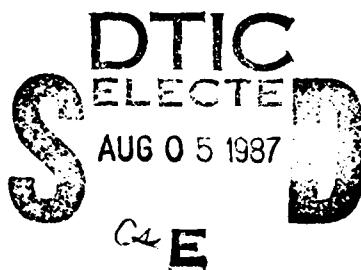
1a. REPORT SECURITY CLASSIFICATION		1b. RESTRICTIVE MARKINGS			
UNCLASSIFIED					
2a. SECURITY CLASSIFICATION AUTHORITY		3. DISTRIBUTION / AVAILABILITY OF REPORT			
		Approved for public release; distribution is unlimited.			
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE					
4. PERFORMING ORGANIZATION REPORT NUMBER(S)		5. MONITORING ORGANIZATION REPORT NUMBER(S)			
DTNSRDC/PAS-86/44					
6a. NAME OF PERFORMING ORGANIZATION	6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION			
David Taylor Naval Ship Research & Development Center	Code 2741				
6c. ADDRESS (City, State, and ZIP Code)		7b. ADDRESS (City, State, and ZIP Code)			
Bethesda, MD 20084-5000					
8a. NAME OF FUNDING / SPONSORING ORGANIZATION	8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER			
Naval Sea Systems Command	PMS 396T				
8c. ADDRESS (City, State, and ZIP Code)		10. SOURCE OF FUNDING NUMBERS			
		PROGRAM ELEMENT NO	PROJECT NO	TASK NO	WORK UNIT ACCESSION NO
Washington, D.C. 20362		N/A	N/A	N/A	DN 506 553

11. TITLE (Include Security Classification)
SOUND POWER MEASUREMENTS IN AIR IN THE NEAR FIELD OF SOUND SOURCES USING THE SOUND INTENSITY METHOD (UNCLASSIFIED)

12. PERSONAL AUTHOR(S)
Polak, John Roger

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Final	FROM 850301 TO 851001	1986 October	66

16. SUPPLEMENTARY NOTATION

17.	COSATI CODES		18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Sound intensity Airborne measurements
			Sound power Reactivity
			Sound pressure

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This study reports on the use of the sound intensity method for finding the sound power output of acoustic sources in air. The sound intensity principle has been under much study in recent years. More information can be obtained about the acoustic properties of sound sources with sound intensity measurements than from sound pressure measurements.

Sound power is the acoustic energy output in watts of a sound-producing source. Sound power can be determined with an array of pressure sensing transducers placed around a source in an anechoic chamber, as specified in the International Standards Organization (ISO) standard 3744-1981 (E). In contrast, sound intensity can be used to measure sound power by measuring the intensity output of the source in watts/meter^2 over a closed surface and using the definition of sound power (intensity X area) to find sound power. The advantages of the sound intensity method are

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT		21. ABSTRACT SECURITY CLASSIFICATION		
☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☒ DTIC USERS		UNCLASSIFIED		
22a. NAME OF RESPONSIBLE INDIVIDUAL		22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL	
J. R. Polak		(301) 267-3742	Code 2741	

Block 19 (Continued)

that one measuring probe is used, which consists of two closely placed pressure sensing transducers: no anechoic chamber is needed; the measurements can be done in the near field; and background noise can be present. Disadvantages are that no standards exist yet and that the phase response between the two transducers in the probe must match closely, either through quality transducers or by careful calibration.

The two methods of determining sound power (the ISO standard sound pressure method 3744-1981 (E) and the sound intensity method) were systematically compared. In addition, a second set of tests was conducted to qualify the effects of environmental reactivity on sound power measurements using the intensity method.

The tests showed that the sound power results from the sound intensity method, even in fairly adverse environments, were comparable to results obtained using the ISO method in most situations. If the true phase difference between the two transducers is very small, as at very low frequencies and in very adverse environments, the sound intensity method fails. Results also showed that to avoid near field effects at low frequencies, the distance between the sound source and the intensity probe should be at least three times the transducer spacing in the intensity probe. The environmental limits can be found from the reactivity, which is defined as the difference between sound intensity and sound pressure levels at the measurement location.

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CONTENTS

FIGURES

TABLES

ABBREVIATIONS AND SYMBOLS

A   Area (meter^2)

BK   Bruel and Kjaer

c   Sound velocity (meter/second)

dB re   decibel with reference to

FFT   Fast Fourier Transform

G_{12} Complex cross spectrum between channels 1 and 2 .

f   frequency (cycles/second (Hz))

H_{12} Transfer function

H'_{12} Phase correction factor

I   Sound intensity (watt/meter^2)

ISO   International Standards Organization

L_I Sound intensity level (decibel with reference to 1 picowatt/meter^2)

L_P Sound pressure level (decibel with reference to 20 micropascals (for air))

L_W Sound power level (decibel with reference to 1 picowatt)

p   Sound pressure (Pascal)

pW   picowatt

r   Transducer (microphone) spacing (meter)

W   Sound power (watt)

θ phase (degree)

u   Particle velocity (meter/second)

uPa   micropascal

$\emptyset$ equipment phase mismatch (degree)

ϱ Fluid density (kilogram/meter^3)

ω angular frequency ($2\pi f$) (radians/second)

Units in parathesis are typical units used in this report

ABSTRACT

This study reports on the use of the sound intensity method for finding the sound power output of acoustic sources in air. The sound intensity principle has been under much study in recent years. More information can be obtained about the acoustic properties of sound sources with sound intensity measurements than from sound pressure measurements.

Sound power is the acoustic energy output in watts of a sound-producing source. Sound power can be determined with an array of pressure sensing transducers placed around a source in an anechoic chamber, as specified in the International Standards Organization (ISO) standard 3744-1981(E). In contrast, sound intensity can be used to measure sound power by measuring the intensity output of the source in watts/meter^2 over a closed surface and using the definition of sound power (intensity X area) to find sound power. The advantages of the sound intensity method are that one measuring probe is used, which consists of two closely spaced pressure sensing transducers; no anechoic chamber is needed; the measurements can be done in the near field; and background noise can be present. Disadvantages are that no standards exist yet and that the phase response between the two transducers in the probe must match closely, either through quality transducers or by careful calibration.

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The tests showed that the sound power results from the sound intensity method, even in fairly adverse environments, were comparable to results obtained using the ISO method in most situations. If the true phase difference between the two transducers is very small, as at very low frequencies and in very adverse environments, the sound intensity method fails. Results also showed that to avoid near field effects at low frequencies, the distance between the sound source and the intensity probe should be at least three times the transducer spacing in the intensity probe. The environmental limits can be found from the reactivity, which is defined as the difference between sound intensity and sound pressure levels at the measurement location.

ADMINISTRATIVE INFORMATION

1

ACKNOWLEDGMENT

Special thanks is given to Dr. Louis T. Ho for his support in the management and completion of this project.

INTRODUCTION

PURPOSE OF STUDY

The purpose of this study was to determine the applicability of present knowledge to real life sound power measurements and to find some guidelines. The work reported here was confined to airborne measurements. The objectives were:

1. To measure sound power using the intensity method and to compare the accuracy of this method to that using the usual sound pressure method.

2. To find the maximum level of background noise that can be tolerated in sound power measurements using the intensity method and to find a way of determining if a particular acoustic environment is acceptable.

3. To see how close to the source one can measure when determining sound power using the sound intensity method.

Most of the testing was done at low frequencies since measurements of rotating machinery was desired. Most types of rotating machinery produce noise at low frequencies, as low as a few hertz.

BASICS OF THE SOUND INTENSITY METHOD

Sound power is the amount of sound energy emitted by a source. Sound intensity is the amount of sound energy passing through a unit area. In recent years the sound intensity method has become a more attractive measurement tool because it allows a more thorough description of the sound source than can be made with the use of sound pressure

measurements. Examples for which sound intensity measurements are useful include localizing sound sources, mapping the surface of a sound source for energy output, finding the transmission loss and absorption of acoustic materials, finding the radiation efficiency of a sound source, and in determining the sound power output of a sound source in less than anechoic environments. All these uses are possible because the transducer arrangement used in sound intensity measurements is directional in response.

Sound intensity (I) is a vector quantity consisting of the product of the time averaged instantaneous sound pressure (p) and the instantaneous particle velocity (u) at a point.

$$I = \overline{pu} \quad \text{watts} \tag{1}$$

where $\overline{pu}$ = time averaged product.

Sound pressure is easily measured by using a variety of standard pressure sensing transducers. The difficulty is in measuring the particle velocity. Transducers that can measure particle velocity have been developed recently but are not widely available. These velocity transducers are limited in frequency range, and they are expensive. Another method of sound intensity measurement is the use of two pressure sensing transducers spaced close together with the axis drawn through the transducer-sensing elements pointed in the desired measurement direction. The signals from each transducer are run into separate channels of a dual channel Real Time or Fast Fourier Transform (FFT) spectrum analyzer. The tests described in this report used FFT spectrum analyzers with microphones as the pressure sensing transducers.

For the use of FFT analyzers with the two-microphone sound intensity measurement probe, the cross spectrum between the two-microphone channels is determined. The

3

method of calculation can be found in Gade[1] and Stusnick.[2] Results of the method are given in Eq. 2:

$$I = - \frac{|G_{12}| \sin\theta_{12}}{\rho \omega \cdot r} \quad \text{watts} \tag{2}$$

where

$|G_{12}|$ is the cross spectrum magnitude between channels 1 and 2,

θ_{12} = phase between channels 1 and 2 (cross spectrum phase angle or sound field phase difference)

ρ = fluid density,

ω = angular frequency, and

r = microphone spacing.

To convert to a log scale in decibels the following is done:

$$L_I = 10 \log_{10}\left(\frac{I}{I_{ref}}\right) \quad \text{db re Iref}, \tag{3}$$

where

L_I = Sound intensity level, and

$I_{ref} = 1 \times 10^{-12} \text{watts/meter}^2$ for air,

$= 6.5 \times 10^{-19} \text{watts/meter}^2$ for water.

At very low frequencies with small microphone spacings the phase difference is quite small. Highly reactive fields also reduce the phase difference between the two microphones at any frequency (Appendix A). If the two microphone channels are not phase matched

exactly, an error results in measuring the phase difference. This causes an error in the measured sound intensity. This phase error will be referred to as the system phase mismatch. Appendix B covers some methods of phase calibration.

The magnitude $|G_{12}|$ can be made accurate with the use of quality measurement systems. A careful magnitude calibration is made for each microphone using standard calibrators. The calibrated sensitivity for each microphone is then input into the analyzer.

Another limiting factor which arises in the cross-spectrum approach is the use of the finite difference approach in the derivation of sound intensity using the two-microphone method. This approach causes errors when the microphone spacing is large compared to the wavelength of the sound waves being measured (Thompson and Tree[3]). The effect on the sound intensity measurement of the use of particular intensity probe configurations is covered below under "Sound Intensity Measurement Systems."

Errors also result when the acoustic intensity at each microphone in the probe is different, as when measuring very close to the sound source in the near field. This is known as near field error.

SOUND INTENSITY MEASUREMENT SYSTEMS

A typical sound intensity measurement system using the cross-spectrum method is shown in Fig. 1.

Two pressure-measuring transducers (microphones for airborne measurements) are spaced a finite distance apart in a support. The measurement surfaces, such as the membranes in condensor microphones, can be facing each other or side by side. The face-to-face setup is said to be better because there is less sound field interference at high frequencies. A spacer is needed in the face-to-face method to determine the accurate placement of the acoustic center between the microphone faces (Pleeck and Peterson[4]).

5

Post Processor
(Controlling Computer)

2-Channel
Spectrum Analyzer

2-Channel Amplifier

Sound Intensity Probe

Microphones
with Pre-amplifiers

Sound Source
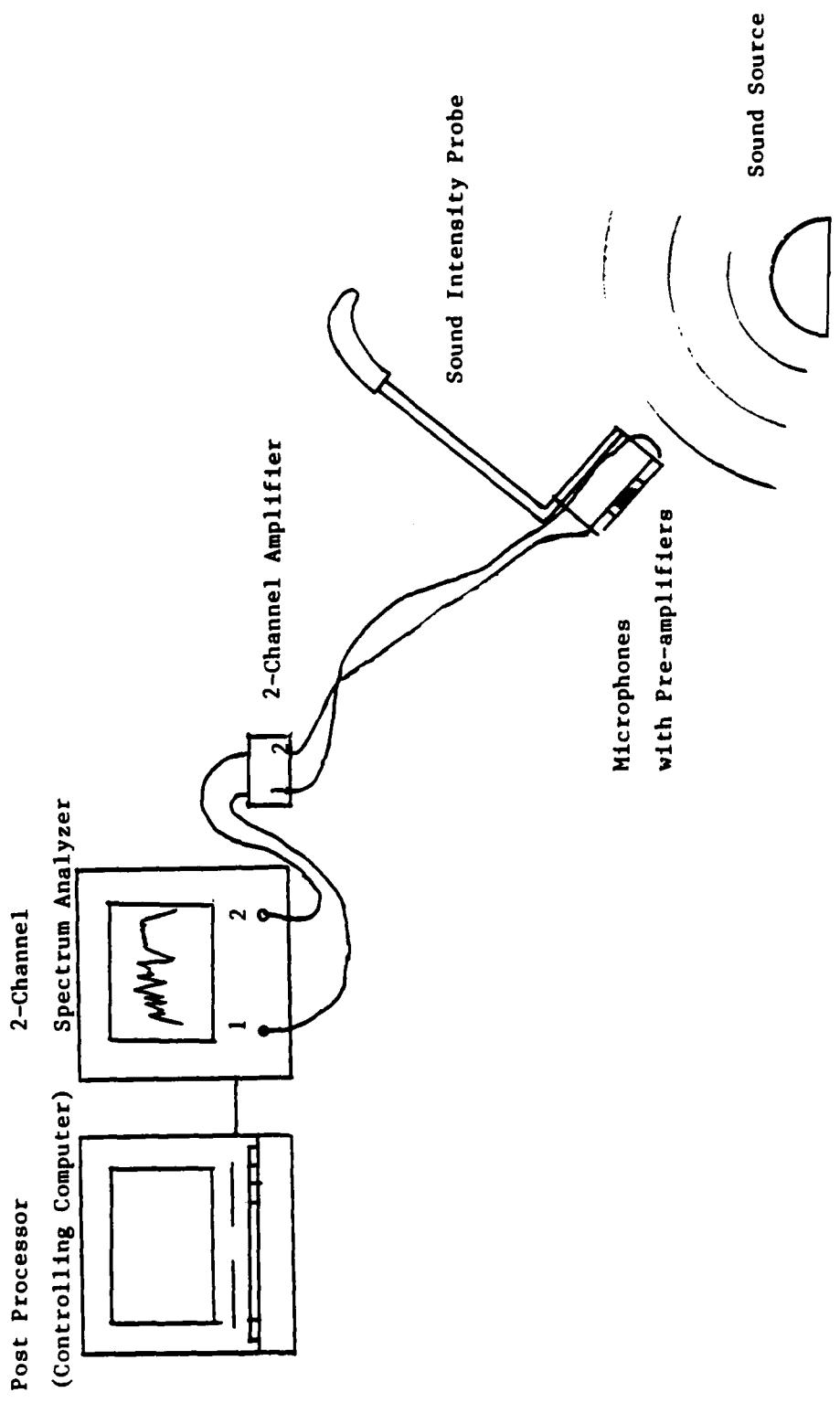
Fig. 1. Typical sound intensity measurement setup.

The interference problem can be reduced for either setup by using small-diameter microphones at high frequencies. Larger microphone measuring surfaces are better for low frequencies due to better sensitivity.

The microphone spacing is dictated by the frequency range of interest. The low frequency limit for any spacing is set by the phase mismatch error. Some error will be present even after phase calibrations, since such calibrations are not perfect. Large spacings increase the actual phase difference measured, thus reducing the effects of phase mismatch-induced error. This extends the low frequency limit. However, a large spacing reduces the high frequency limit due to finite difference error. In this case, a smaller microphone spacing will extend the high frequency limit.

Table I gives some example frequency ranges for different spacings at two phase mismatches in air using the face to face setup (Gade etal[5]).

The reactivity is the difference between the sound pressure levels and the sound intensity levels at the measurement location. Highly reactive fields such as a reveberant room, close to a vibrating surface, or areas of high background noise reduce the phase differences between the two channels from those expected from a plane wave. This raises the low frequency limit for a probe configuration. Appendix A discusses this subject in more detail.

Table I. Intensity probe configuration frequency ranges.
No near field error is assumed.

Microphone Spacing	Phase Mismatch (degrees)	Reactivity* (L_I-L_p) (dB)	Frequency Range (Hz)
6 mm	0.1	0	80–10000
		-3	140–10000
		-10	600– 10000
	0.3	0	250–10000
		-3	500–10000
		-10	3000–10000
12 mm	0.1	0	40–5000
		-3	80–5000
		-10	400–5000
	0.3	0	125–5000
		-3	250–5000
		-10	1250–5000
50 mm	0.1	0	10–1250
		-3	20–1250
		-10	100–1250
	0.3	0	32–1250
		-3	64–1250
		-10	300–1250

*L_I = Sound intensity level db re 1 pW   Table above is for airborne
 L_p = Sound pressure level db re 20 uPa   measurements

The intensity probe is directional by the nature of the transducer arrangement. Sound coming into the sides is interpreted as having a low intensity. Sound coming from the rear has a negative intensity.

Any phase mismatch alters this directionality because the system measures zero intensity at some position other than 90° to the direction of sound propagation.

The signal processing system to be used must have two-channel capacity. Fast Fourier Transform (FFT) narrow band spectrum analyzers are best since they have aliasing filters built in. The system has to be able to compute the complex cross spectrum. Some

real time spectrum analyzers can compute sound intensity directly (see Appendix C). Some FFT analyzers will compute third octave and octave band values; for others this must be calculated by the post processor.

Post processing is required to calculate the sound intensity with the phase correction factors after the cross spectrum is obtained from the analyzer. The computer can be used to apply the many applications of the sound intensity method.

CALCULATING SOUND POWER FROM SOUND INTENSITY MEASUREMENTS

Sound intensity measurements are useful in finding the sound power of a source. Sound power rates the acoustic source for sound energy output in watts, much in the same way one would rate a light bulb in electrical output.

The most common method of finding the sound power of a source in use today is the ISO 3744-1981 (E) method, which is shown schematically in Fig. 2. In an anechoic chamber, ten microphones are located around a measurement surface enclosing the sound source to be measured. The most used measurement surface is a sphere, or fractions of a sphere with reflecting surfaces. Formulas are used to convert the sound pressure measurements to a sound power measurement. This is possible since sound intensity can be related to sound pressure by the formula below using progressive plane or spherical sound waves.

$$I = \frac{P^2}{\rho c} \text{ watts/meter}^2 \tag{4}$$

Sound power (W) can also be calculated as sound intensity times area (A):

$$W = IA. \tag{5}$$

A closed measurement surface is defined around the source and it is divided up into a number of subareas. The number of subareas is determined by what is neccessary to provide the proper resolution of the sound field around the source. The average sound intensity is measured at each subarea with the intensity probe perpendicular to the measurement surface. The intensity probe can be swept slowly over a subarea's measurement surface

9
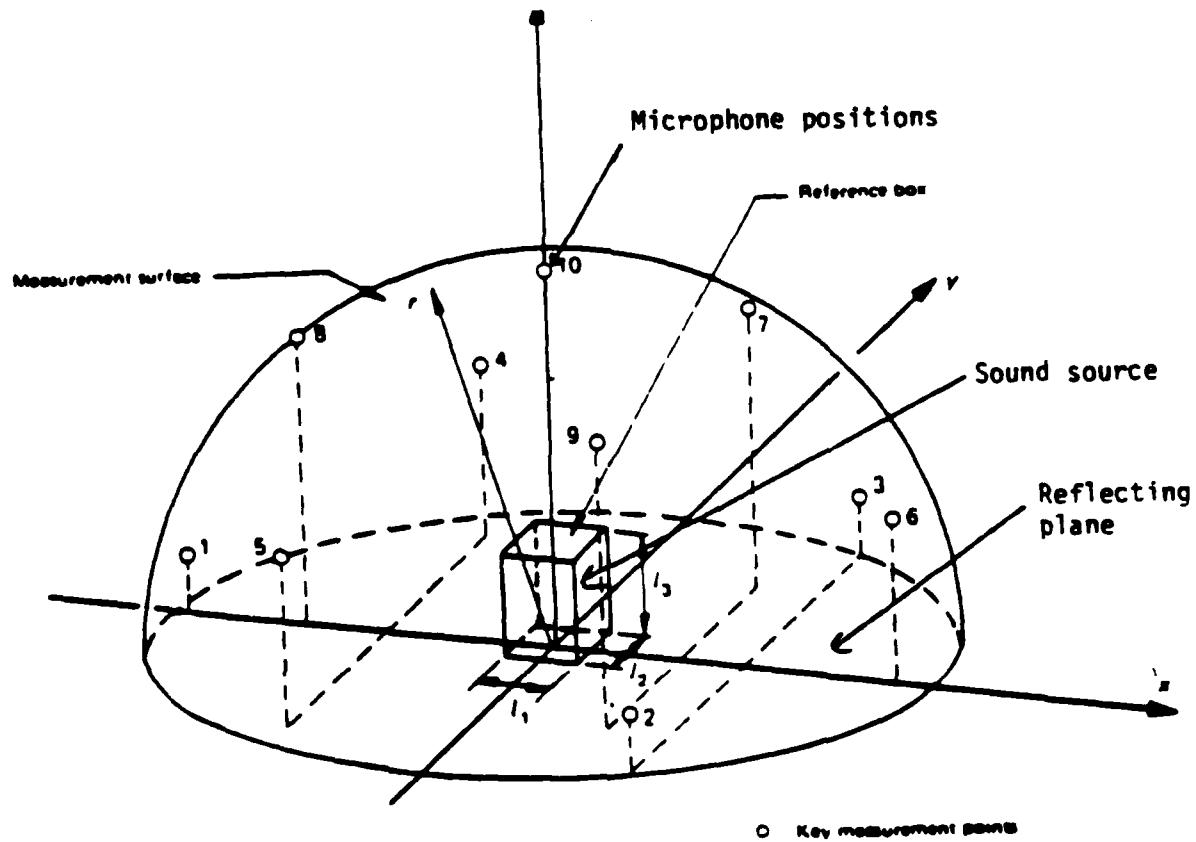
Fig. 2.   ISO 3744-1981 (E) sound power measurement setup.
          The sound pressure measurements from all
          10 microphones are averaged together for
   the sound power determination.
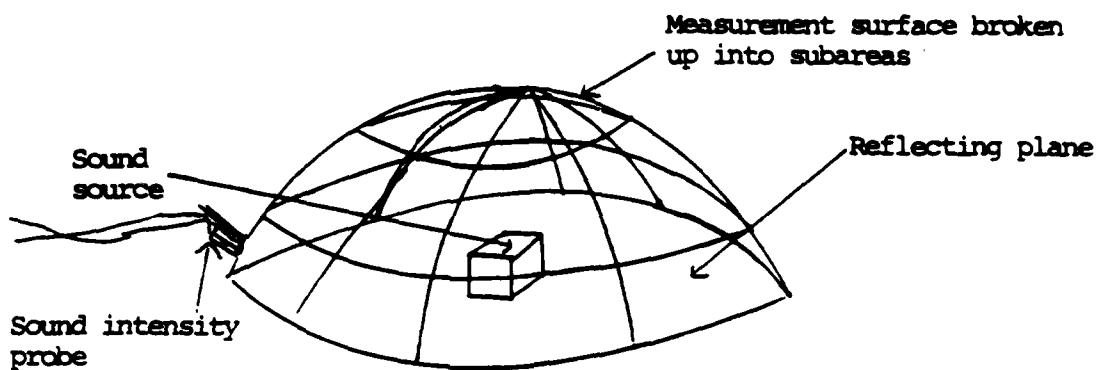
Fig. 3. Setup for sound power measurement with sound
   intensity method.
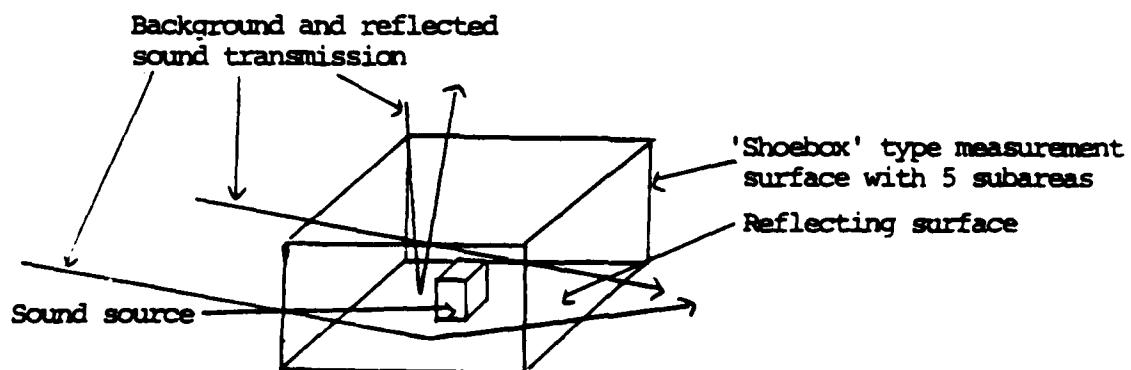
Fig. 4. Background noise cancellation with the use of
         sound intensity to find sound power.

several times while averaging, or can make a single point measurement in each subarea. The sweeping method is preferred. Figure 3 shows the use of the intensity method for measuring sound power. The measurement surface can be of any shape as long as it is a closed surface. Reflecting planes can be used as part of the measurement surface. The sound power is calculated by multiplying the intensity measured for each subarea by the area of that subarea, and then summing all the results for the entire measurement surface.

$$W = \sum_{i=1}^{n} IA_i \,. \tag{6}$$

where n is the number of subareas and A_i defines the area of each subarea.

The beauty of the sound intensity method is that it does not require an anechoic chamber. Any background noise or reflected signals pass through the measurement space. Such undesired noise is measured when entering the measurement volume and cancelled out when measured   leaving the measurement volume, as shown in Fig. 4.

Since no standards exist for sound power determination using the intensity method, verification is usually done by repeating the sound power measurement using twice as many subareas. The desirable minimum distance between the measurement surface and the source depends on the existance of near field effects, the overall environmental reactivity (see Appendix A) over the measurement surface, and the desired frequency range of measurement. The presence of near field effects shows up in the reactivity check, especially at low frequencies. For bad acoustic environments, it is desirable to measure as close to the sound source as possible.

EXPERIMENTS

Because no standard methods exist for using the intensity method for measuring sound power, we did two sets of experiments to better define the accuracy and limits of this method. The first set, Experiment 1, compared measurements using the sound intensity and

12

the sound pressure methods. Experiment 2 tested the use of the sound intensity method to determine sound power in adverse environments close to the sound source in reactive environments. Methods to find the limits of sound intensity use in such environments was tested.

EXPERIMENT 1:
SOUND INTENSITY VS. SOUND PRESSURE APPROACH FOR SOUND POWER DETERMINATION

This experiment compared the accuracy of sound power determination using intensity measurements with the accuracy of the standard sound pressure measurements.

Experimental Setup and Procedure

A Bruel and Kjaer (BK) reference sound source was used for a sound source. Factory phase matched equipment using the BK model 3519 intensity probe with a BK 2032 FFT analyzer measured sound intensity. The BK equipment is reported, by BK, to be phase-matched to better than 0.3°. BK documentation shows around 0.1° phase mismatch below 1000 Hz for the probe. An analyzer check showed the BK 2032's phase mismatch to be 0.1° or less at 0 to 6400 kHz. Measurements taken using the modified switching technique phase calibration described in Appendix B did not improve the results, but sometimes made them worse. The proper apparatus for a plane wave phase calibration was not available.

The sound pressure measurements were taken with 1/2 in. model 4165 BK microphones using a General Radio (GenRad) 2512A single channel FFT analyzer with 1/3 octave synthesis built in. For determining sound power with sound pressure measurements, the ISO 3744-1981 (E) standard was used with ten microphone positions as in Fig. 2.

To determine sound power with sound intensity measurements, a 10 by 40 ft. trailer was converted for laboratory use. Very little background noise was present. A shoebox

13

measurement surface with five subareas was used. The closest distance to the sound source for measurement was 8 in. Figure 5 shows the intensity method setup. The sound power with intensity measurement were verified using a measurement with 10 subareas.

To calculate sound power, measurements from both methods were converted to 1/3 octave band data. The sound pressure conversion was done in the GenRad analyzer. The intensity conversion was done by a computer. Both results were compared to a calibration of the reference sound source done in July 1984 by Cedar Knolls Acoustic Laboratories of Cedar Knolls, New Jersey.

Next we tested how much background noise is tolerable when measuring sound intensity to determine sound power. The idea of this study is to see how much background noise will be cancelled by using sound intensity to determine sound power. The increase of the environment reactivity due to the background noise was also looked at as an effect on sound power measurements.

A large speaker was placed near the measurement area and fed with white noise (see Fig. 6). Two procedures for evaluating the sound field were used. The first was to measure two sound pressure levels over the measurement surface with background noise, one with the reference source turned off and one with the reference source turned on. The second procedure was to measure the overall reactivity over the measurement surface by taking the average, over the measurement surface, of the sound pressure levels and the sound intensity levels. The pressure level was then subtracted from the intensity level to obtain the reactivity of the measurement field. The effect on the cross spectrum phase angle, in the sound intensity/sound power calculation, was determined from Fig. A.1 in Appendix A.

Results and Discussion of Experiment I

Table 2 compares the sound power determinations using the sound pressure and the sound intensity methods without added background noise.
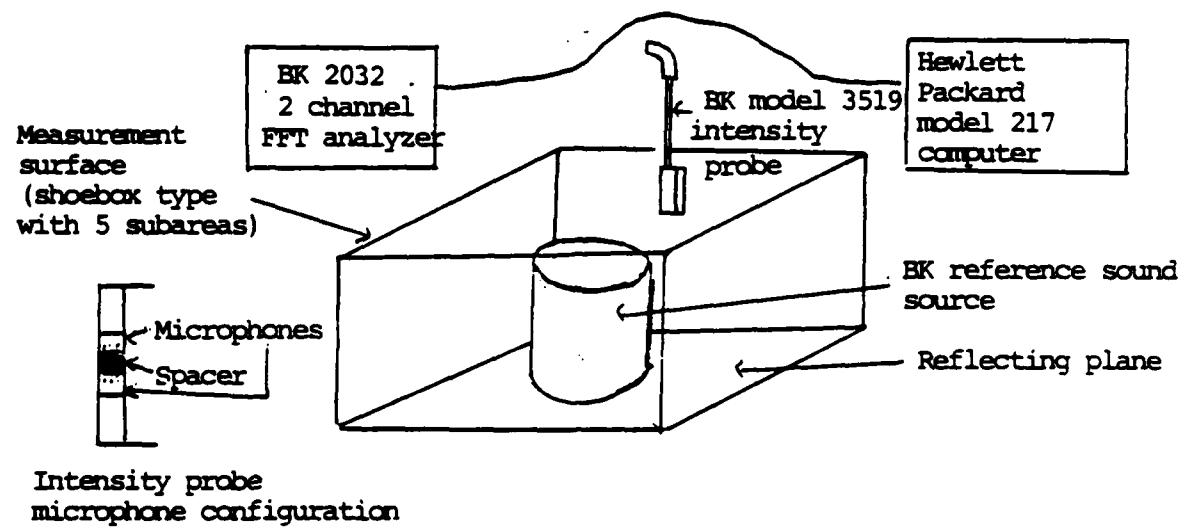
Fig. 5. Experiment 1: Setup used for sound power measurements using the sound intensity method.
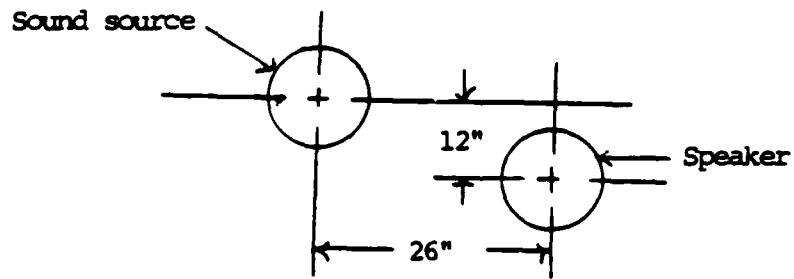
Fig. 6. Experiment 1: Setup used for sound power measurements using the intensity method with background noise. Speaker is facing up level with sound source base.

Table 2.   Comparison of sound power determined from sound
           pressure and sound intensity without added
           background noise.

1/3 Octave Band Number	Center Frequency (Hz)	Sound Power (dB re 1 pW)		
		Cedar Knolls Calibration	Pressure Method	Intensity Method*
23	200	82	79.9	79.3
24	250	82	81.0	81.4
25	315	81	81.3	80.6
26	400	82	80.7	80.5
27	500	82	80.6	79.9
28	630	83	81.2	80.6
29	800	85	83.8	83.7
30	1000	87	85.3	85.1
31	1250	87	86.7	86.4
32	1600	87	85.8	86.1
33	2000	86	85.3	85.0
34	2500	84	81.8	83.3
35	3150	82	81.3	81.3
36	4000	81	83.5	80.1
37	5000	81	83.0	81.0
38	6000	79	81.3	79.4
39	8000	77	78.9	76.7
40	10000	74	77.7	74.0

*The sound intensity method failed below band 23.

16

For the intensity method bands 23 to 28 were taken using 1/2 in. diameter microphones with a 50-mm spacing between the membranes. Bands 29 to 36 were taken with 1/2 in. microphones spaced 12-mm apart. Bands 37 to 40 were taken using 1/4 in. diameter microphones spaced 6-mm apart.

From Table 2, it can be seen that the intensity method matched the pressure method values within 1 dB to band 35. Sound power levels below band 23 were not compared because the intensity method failed due to the reactivity of the measurement environment. Both methods fell 1 to 2 dB below the Cedar Knolls calibrated values at the low frequencies in the table. At band numbers above 35 the pressure method results exceeded the calibrated values while the intensity method stayed with them. To check for repeatability, both the intensity and the pressure tests were rerun twice more, and each time the results were simliar ± 1 dB.

Thus, for the frequency range allowed by the measurement environment, the intensity method was as accurate as the sound pressure method for determining the sound power of the source. Experiment 2 also showed that the sound intensity method agreed with the sound pressure method to frequencies down to 30 Hz in an anechoic room. Above band 35 the sound intensity method appeared to be more accurate. The better accuracy at high frequencies may have something to do with these frequencies being more directional. The reference sound source does not imitate a point source exactly and has some directivity. Since the pressure method averaged all the microphones, this directivity was nullified in the sound power determination. The intensity method picks it up since the measurement surface was broken up into five separate subareas.

It has been suggested that the pressure method is preferable to the intensity method since the pressure method is taken in the far field in an anechoic chamber. The sound field in this case is much less complex as in using the intensity method in the near field. This suggestion is valid mostly at low frequencies, where sound is undirectional and phase

17

matching problems arise with the use of the intensity method. However, an anechoic chamber rated for low frequency work is not often available.

In the next set of tests, the sound power of the reference sound source was measured using the intensity method in the laboratory trailer with background noise present. Figure 7 gives results of the environmental noise check measured using sound pressure measurements. With background noise kept on, the sound pressure levels were measured over the measurement surface with the reference source both on and off. Figure 8 gives the environmental reactivity over the measurement surface with the reference and background sound sources on.

The reactivity check shows reactivities (L_I-L_p) of around 10-12 dB from 800 Hz to 2600 Hz. Reactivities of greater than 15 dB from 400 to 800 Hz and greater than 20 dB between 2600 and 4400 Hz were seen. Reactivity levels of around 4 dB were present above 4400 Hz. With a $0.1°$ to $0.2°$ phase mismatch the sound power measurement (from Appendix A) should be valid at 100 to 400 Hz, 800 to 2600 Hz, and 4500 to 5000 Hz. Above 5000 Hz, finite difference error will arise, since a 12-mm spacing was used between the microphone faces. Between 1600 and 2600 Hz, the reactivity was very close to the maximum allowed for a valid sound power measurement. These values were obtained using a minimum allowed true phase difference of $0.6°$ between the two microphones.

In the sound pressure level environmental check, finding the reference source in the background noise was difficult at any frequency between 400 and 4500 Hz.

Figure 9 shows the sound power results measured with background noise on using the intensity method. The sound power measurement was accurate to within 1 to 2 dB at 150 to 400 Hz, 800 to 1600 Hz, 2000 to 2600 and 4500 to 5000 Hz. At other frequencies, measurements were completely unacceptable with errors in excess of 2 dB.

These tests showed that sound power measureed with the intensity method will most likely be inaccurate when the measurement field becomes reactive to the point of reducing

18
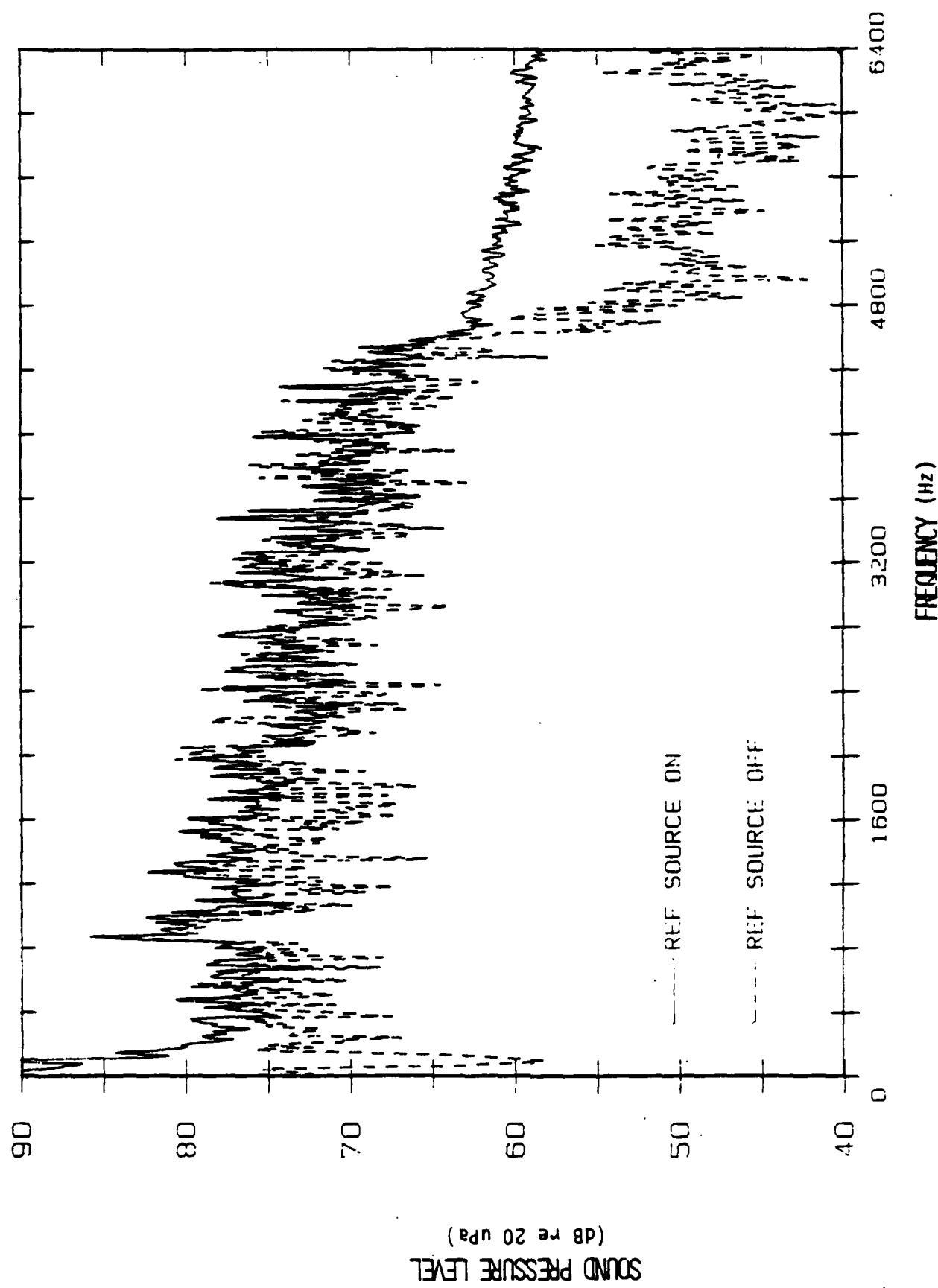
Fig. 7. Sound pressure environmental check with background noise.

PRESSURE LEVEL dB re 20μPa

INTENSITY LEVEL

In trailer 8 inches away

FREQUENCY (Hz)
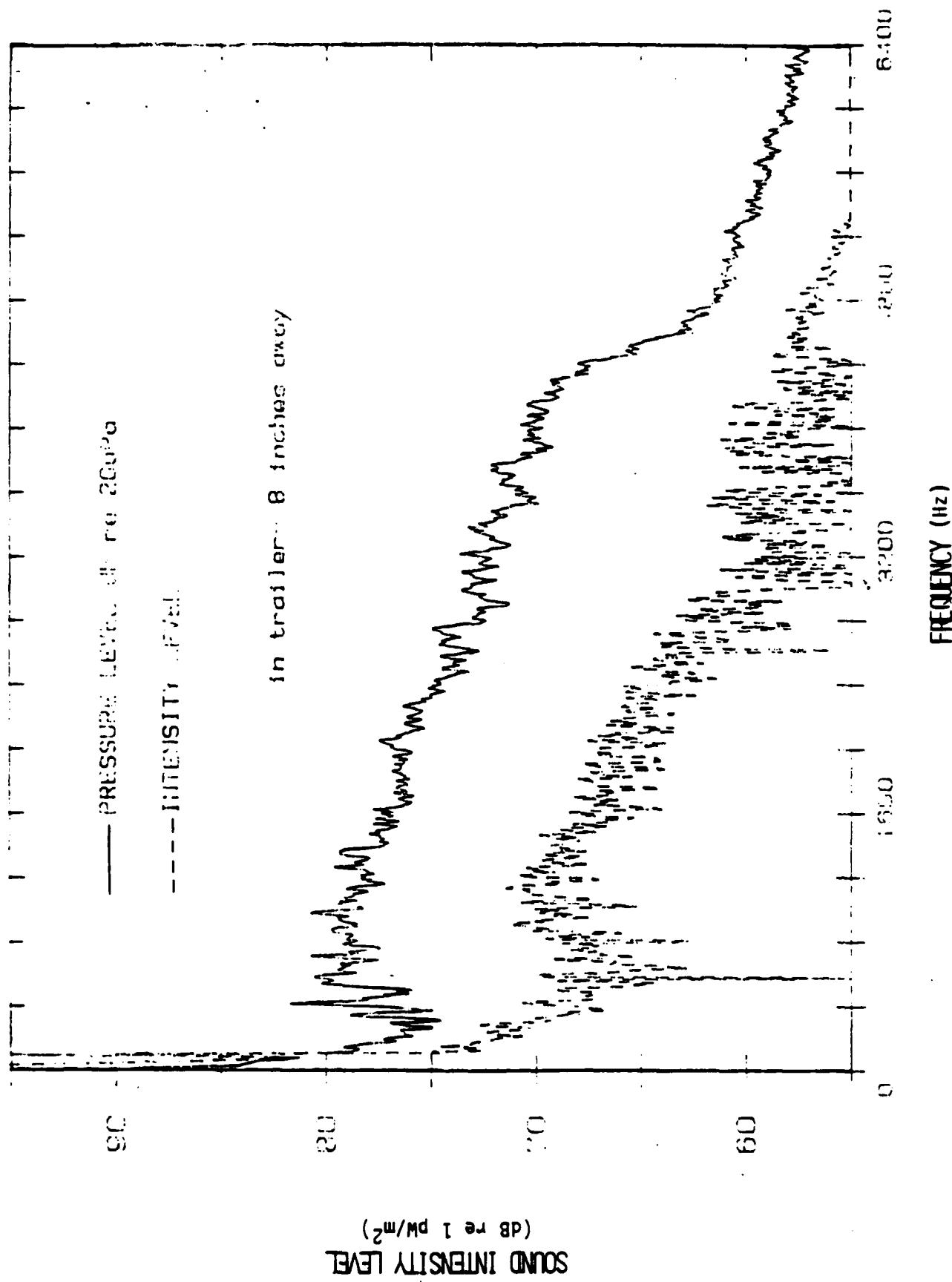
Background Noise Check-Reactivity ise.

SOUND INTENSITY LEVEL
(dB re 1 pW/m²)

20

SOUND POWER LEVEL
(dB re 1 pW)

FREQUENCY (Hz)

BALANCED RED NOISE

WITH NO BACKGROUND NOISE
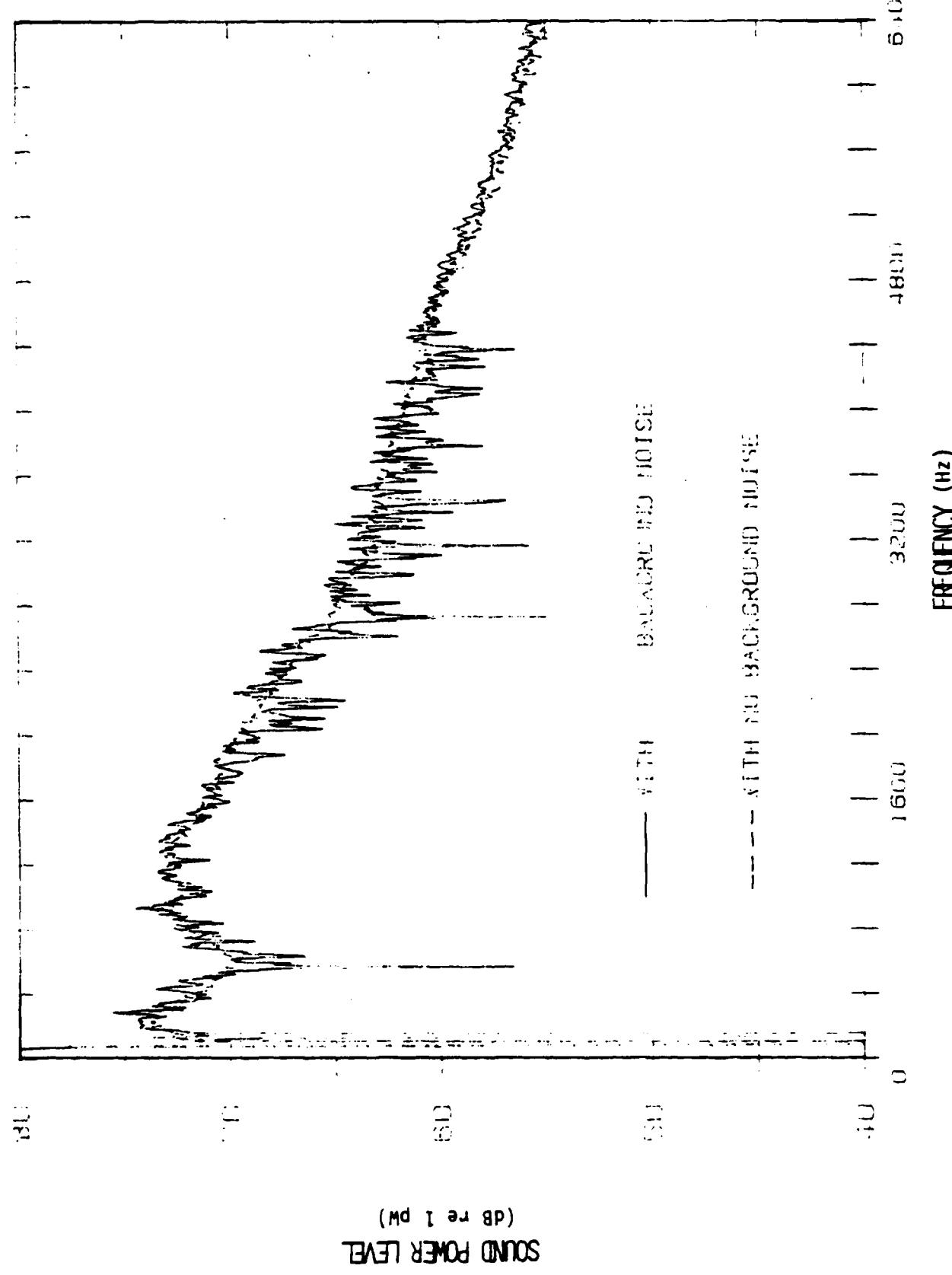
the true phase difference between the microphones to less than three to five times the instrumentation system phase mismatch. With the intensity method, the sound power could often be accurately measured when the sounce source was masked by background noise using sound pressure measurements.

The reactivity measurements did predict fairly well when the sound power measurement would be accurate, even when it was difficult to pick the source out of the background noise with sound pressure measurements. In experiment 2 we investigated in more detail the effects of reactivity in the acoustic environment.

EXPERIMENT 2: MEASURING SOUND POWER VERY CLOSE TO THE SOUND SOURCE

Experiment 2 was designed to reveal the effects of obtaining sound power measurements using the sound intensity method very close to the sound source. Such close-in measurement is often necessary with weak sound sources or in poor acoustic environments.

Two problems arise with close-in measurements. The first is that the sound field becomes more reactive, thus reducing the true phase difference in the sound intensity measurements. The second is that the outgoing intensity component does not remain the same at each of the two transducer locations. This is known as near field error. The first problem is accounted for by taking reactivity measurements as described in Appendix B and finding the frequency ranges applicable for the intensity probe configuration, as we did in experiment 1. The second problem has been described with Table 3 (Gade[1]).

22

Table 3. Distance from source required to avoid near field effects (Gade[1]).

Source Type	Distance from Acoustic Center of Sound Source (Minimum for 1 dB error)*
Monopole	1.1r
Dipole	1.6r
Quadrapole	2.3r

*The acoustic center is usually behind the physical surface.
r = transducer spacing

Experimental Setup and Procedure

A "Little Giant" pressure/vacuum pump was used as the sound source to simulate actual machinery. This pump consists of a 1/12 hp electric motor driving a small one cylinder compresser. The sound power of the entire pump/compresser unit was taken using first the sound pressure method in an anechoic room and then the intensity method in a variety of environments. The pressure method used the BK 2032 analyzer with BK model 4165 condensor microphones and BK model 2807 microphone power supplies. The setup in Fig. 2 was used. The measurement system for the intensity method consists of a BK model 3519 sound intensity probe, BK model 2807 microphone power supplies, BK model 2032 dual channel FFT analyzer, and a model 217 Hewlett Packard computer system (see Fig. 10). For some of the experiments, a Hewlett Packard model 3900 instrumentation tape recorder was used with 1/4 in. recording tape. This recorder produced negligible phase mismatch in the FM channels when Ampex 797 instrumentation tape was used. In the intensity probe, 12-mm and 50-mm spacings were used between the microphone membranes in a face-to-face configuration. A spacer was placed between the microphones, thus the transducer (microphone) spacing is the same as the spacer length referred to in following discussions. A frequency range of 0 to 800 Hz was picked to provide better resolution at low frequencies. The "Little Giant" pump did not produce much acoustic output above 1000 Hz.

A Hewlett Packard model 9000 tape recorder
was used for the sound power measurements and
the associated reactivity check in the tool shed.
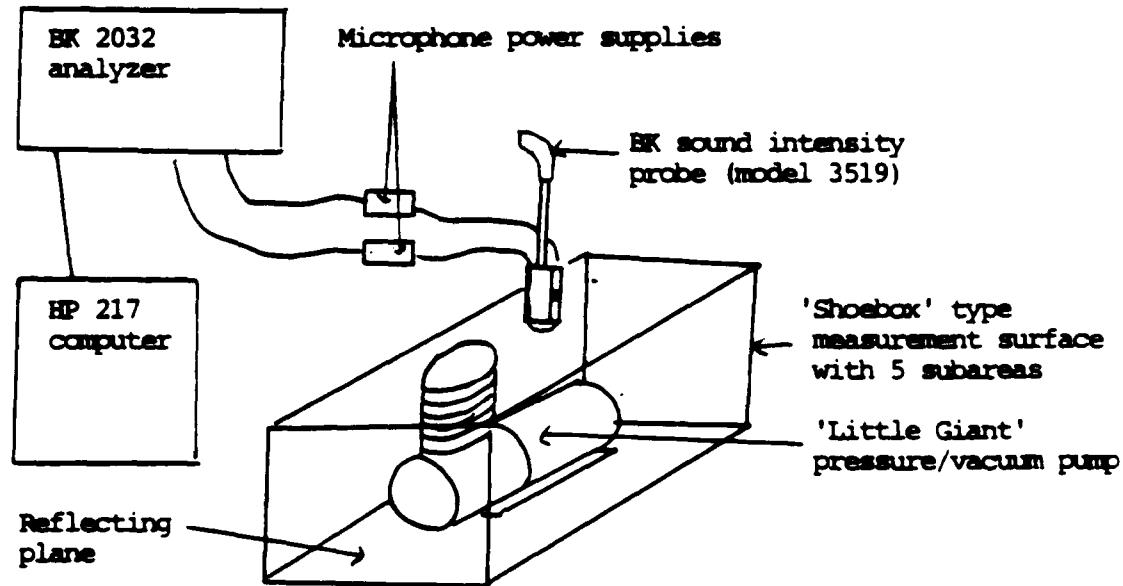
Fig. 10. Experiment 2: Setup for sound power measurements
using sound intensity.

The experiment using the intensity method of finding the sound power was run in three different environments. The first was in the anechoic room. The second was in a small (10 X 12 ft.) tool shed consisting of thin metal walls coated with 1/2 in. thick styrofoam insulation. No background noise other than normal ambient noise was introduced. The shed contained a fair amount of piping in storage, thus making the acoustic environment somewhat reveberant. The third environment was in the laboratory trailer used for experiment 1 with background noise introduced by the BK reference sound source standing nearby.

The sound power measured with the intensity method was based on a five subarea shoebox-type closed measurement surface with a bottom reflecting plane. Minimum distances to the sound source for measurement were 12, 6, and 3 in. in the anechoic room and 6, 4, and 3 in. in the tool shed and trailer. The baseline sound power used was the 12 in. distance in the anechoic room using a 50-mm microphone spacing. This baseline was verified with sound power measurements using the pressure method and the intensity method with ten subareas. The 3 in. distance sound power results were also verified using 10 subareas for the worst condition, with background noise present in the trailer. It was then assumed that other conditions could also be verified using 10 subareas, though these checks were not done. Figure 10 illustrates the measurement setup.

Results and Discussion of Experiment 2

The results were plotted using the pump fundamental and harmonic frequencies for clarity. Figure 11 show the results of the verification of the baseline sound power measurement, and Fig. 12 the verification of the "worst case" 3 in. measurement. Some error was allowed since the pump is not completely steady. The sound power mesurements for each condition was generally within 2 dB.

Figures 13, 14, 15, 16, and 17 show the results of the reactivity checks of the measurement environments involved in this experiment. They are discussed in more detail later. For the reactivity checks, the 50-mm spacer was used to minimize phase mismatch error. The reactivity checks then were repeated using the 12-mm spacer to check for errors due to near field effects. Note that some reactivity is introduced with the use of a "shoebox" measuring surface since the intensity probe does not always remain pointed toward the sound source.

The first tests were run to see if the modified switching phase calibration technique described in Appendix B would improve the sound power results, especially close to the source. The equipment used for the measurement was already phase matched to 0.1° to 0.2° or less. The test was done in the anechoic chamber. The results showed that the phase calibration did not always improve the results, and sometimes made them worse.

Next, the actual experiment was carried out. Figures 18, 19, 20, 21, 22, and 23 show the results. Again, only the maximum value of the compressor piston-induced fundamental frequency and its harmonics were plotted for clarity. Table 4 summarizes the results. The experimental low frequency limit was determined from the actual sound power measurements. Each measurement was compared to the baseline measurement. The predicted low frequency limit was determined from the reactivity checks on each measurement setup. Figure A.1 in Appendix A was used to predict the low frequency limits from the data obtained during the reactivity checks. An exception was the 12 in. distance for the anechoic environment. This low frequency limited was predicted from Table 1.

26
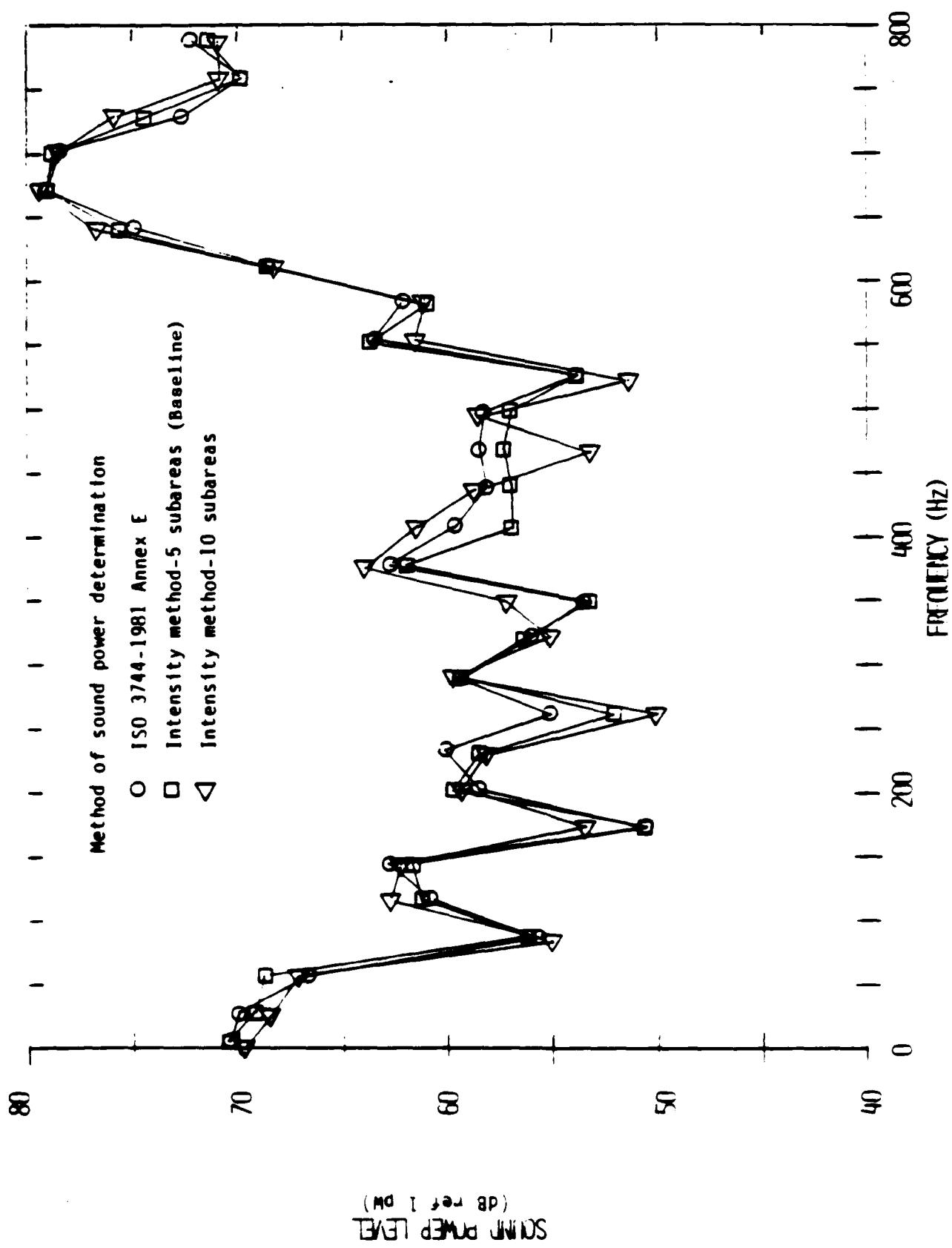
Fig. 11. Verification of baseline sound power measured with the intensity method in an anechoic chamber. Microphones spaced 50-mm apart were at a 12 in. minumin distance from sound source.
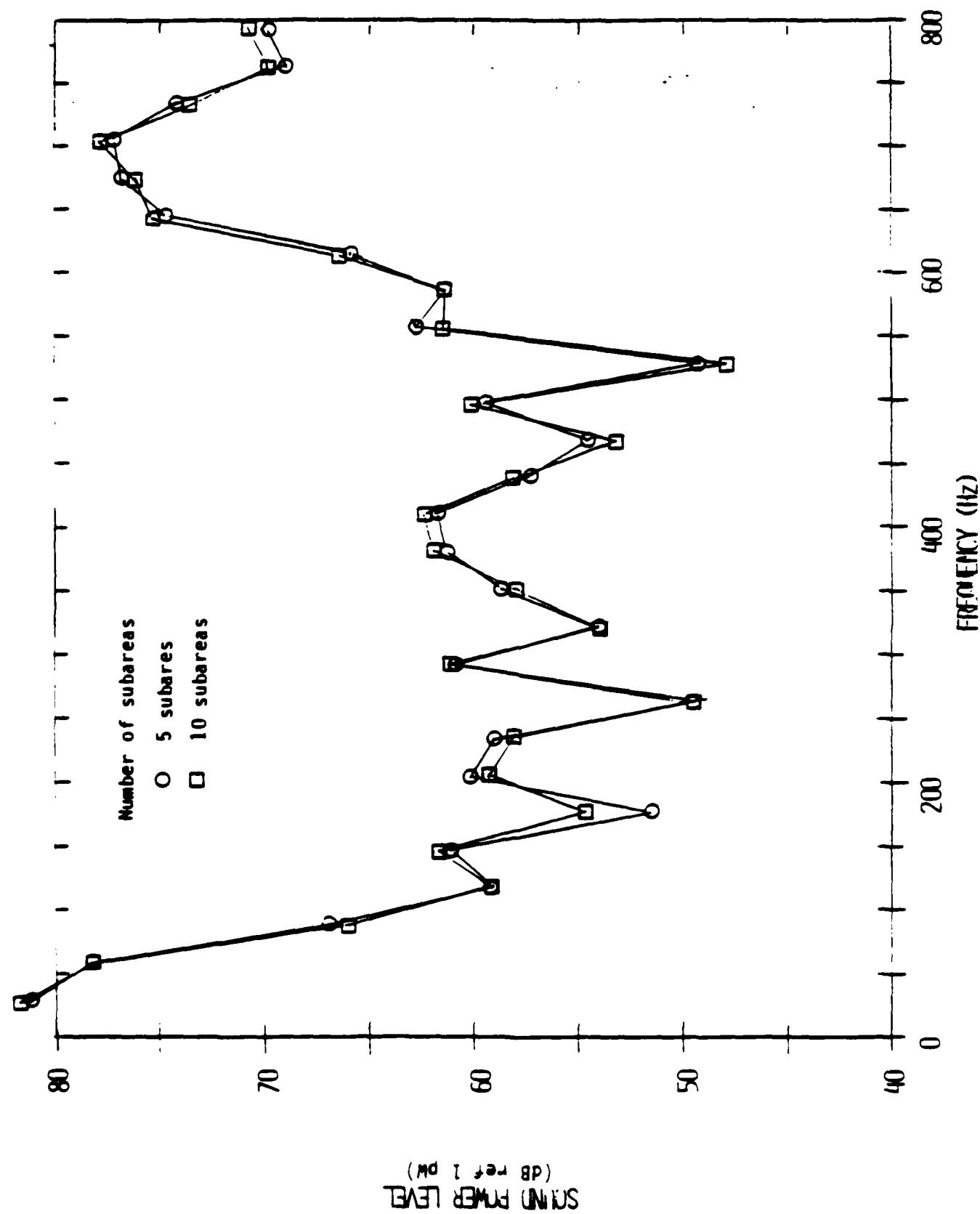
Fig. 12. Verification of "worst case" sound power measurement. Intensity method used with 12-mm microphone spacing. Distance from sound source is 3 in.

28
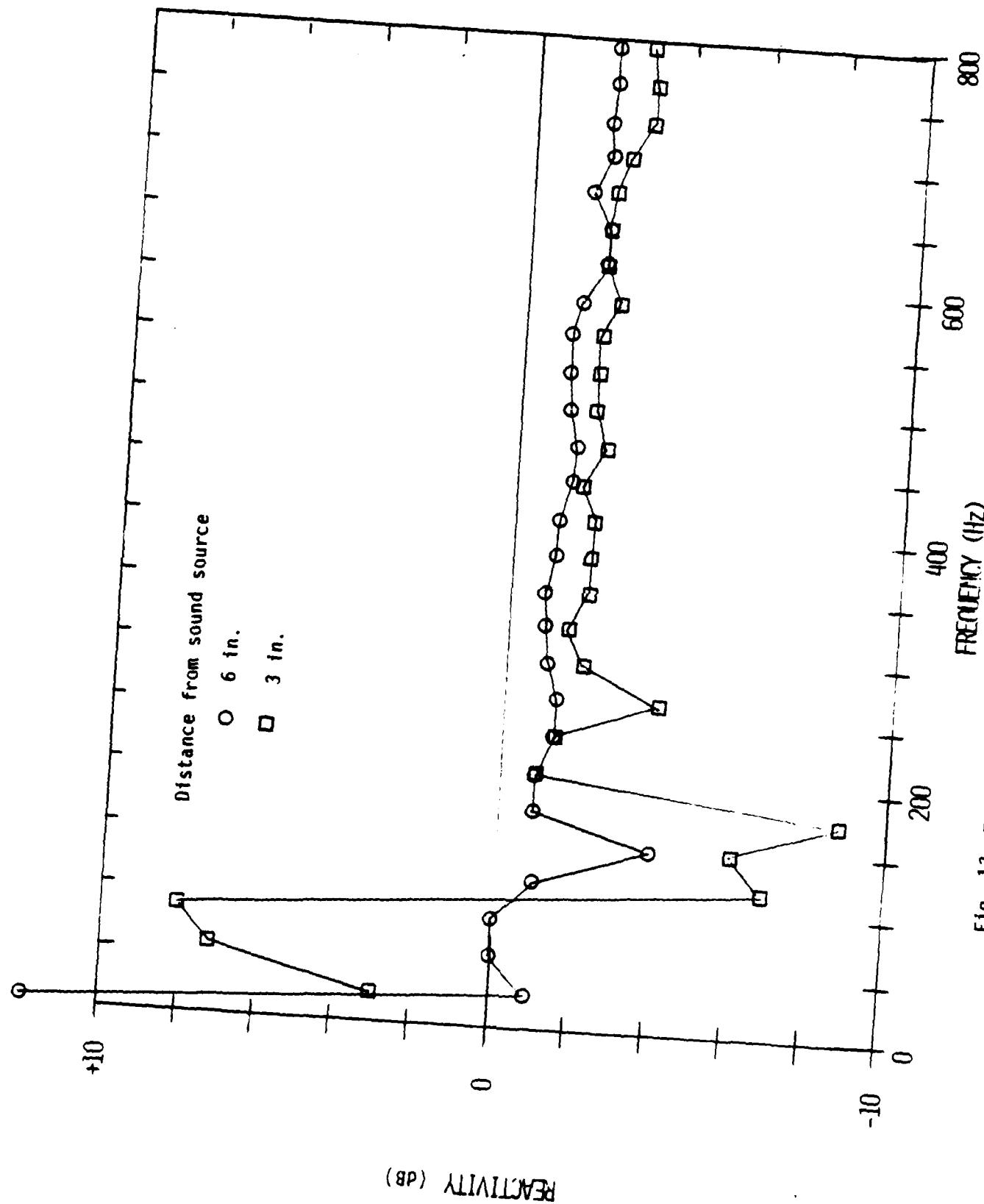
Fig. 13. Environmental reactivity in anechoic chamber (50-mm spacer).
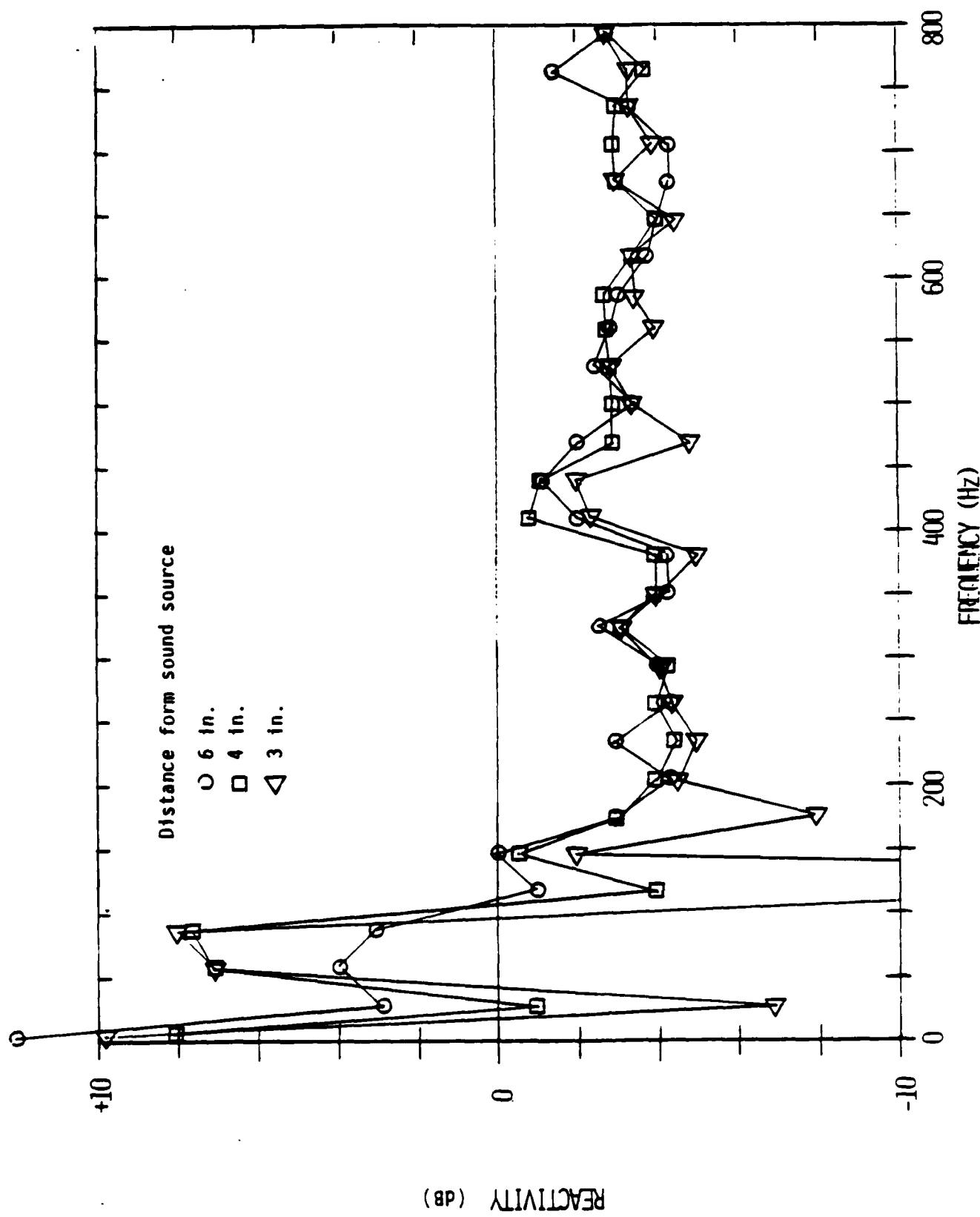
Fig. 14. Environmental reactivity in tool shed (50-mm spacer).

30
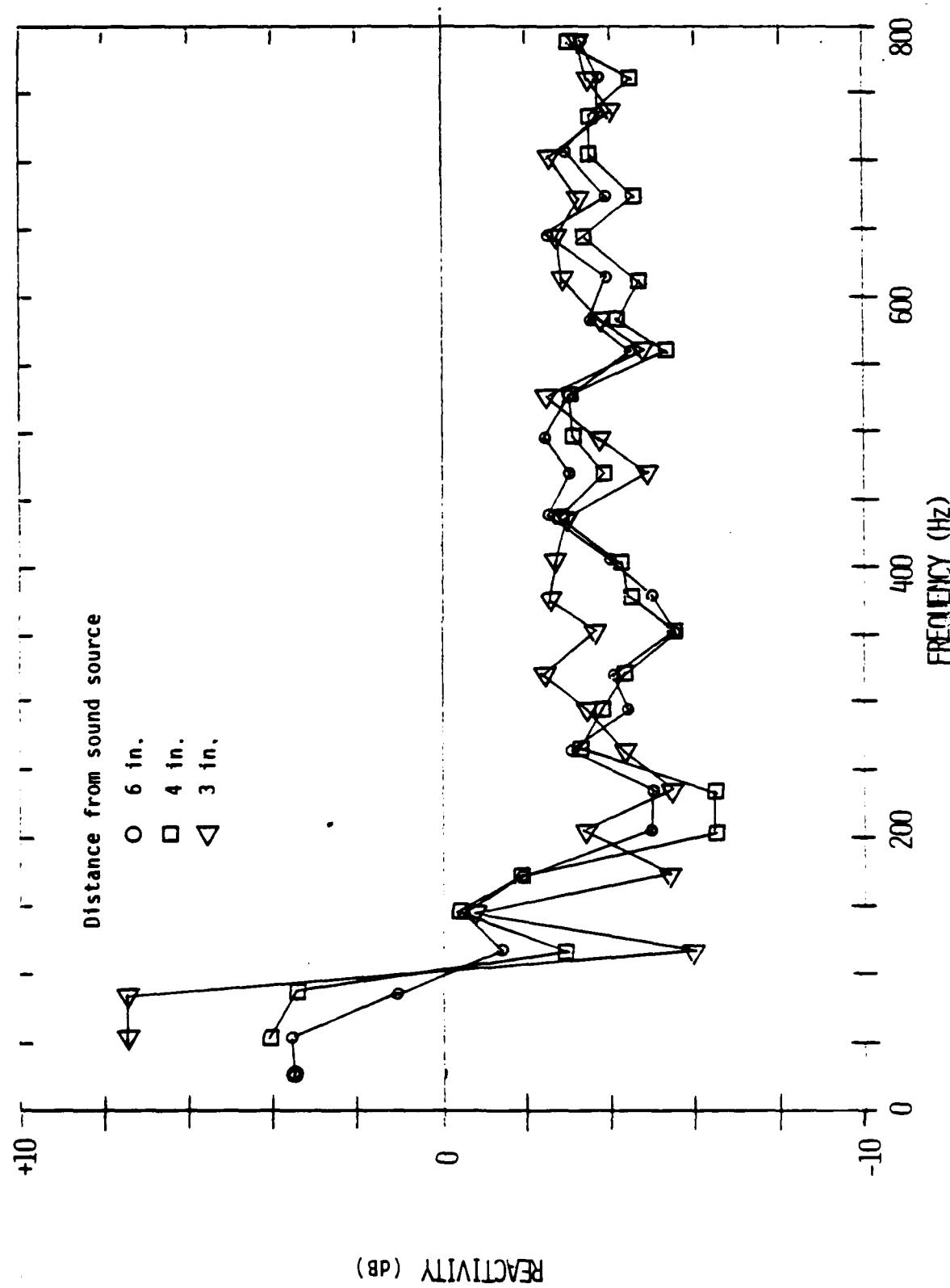
Fig. 15. Environmental reactivity in tool shed (12-mm spacer).
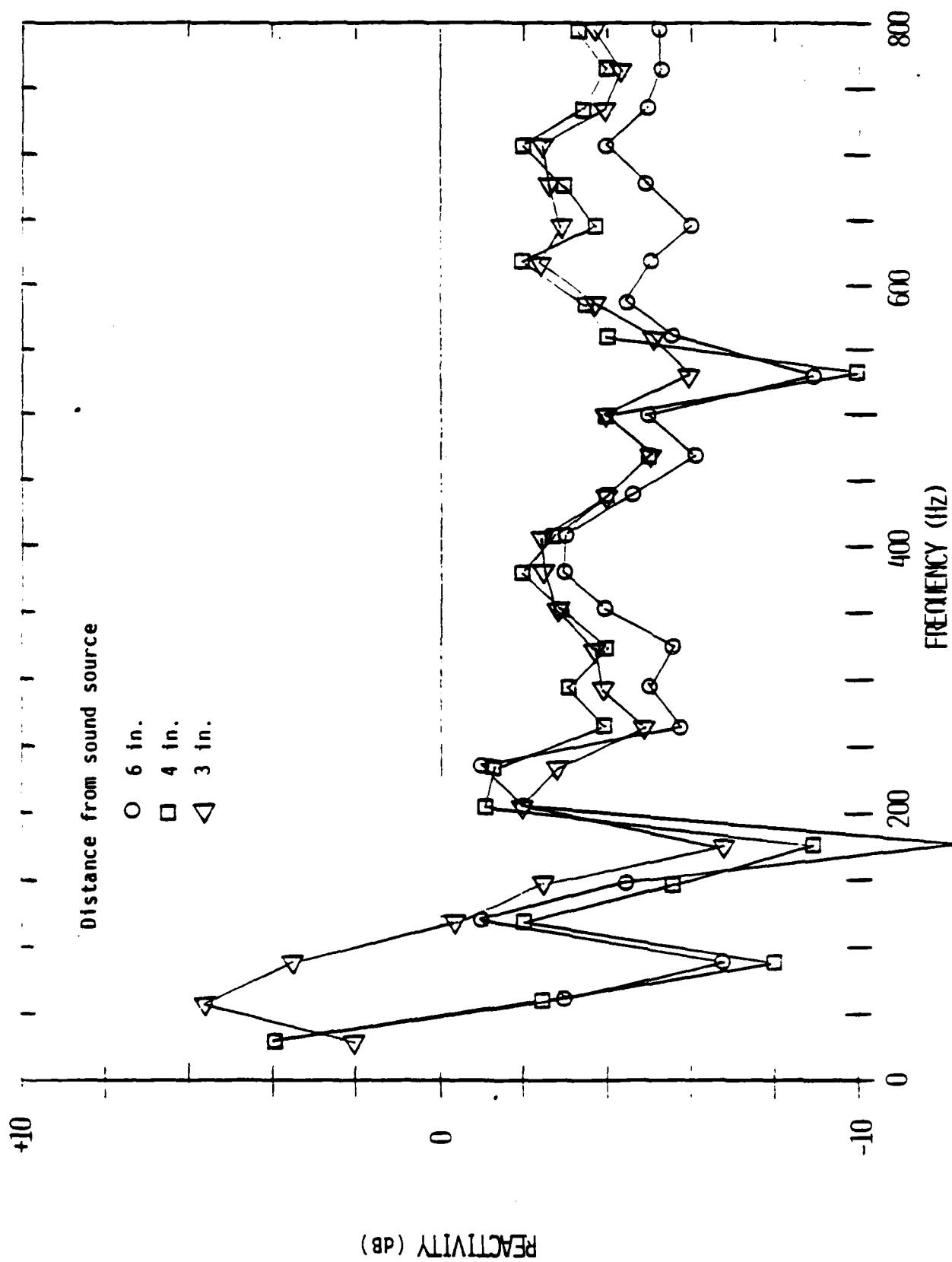
Fig. 16. Environmental reactivity in trailer with background noise (50-mm spacer).

32
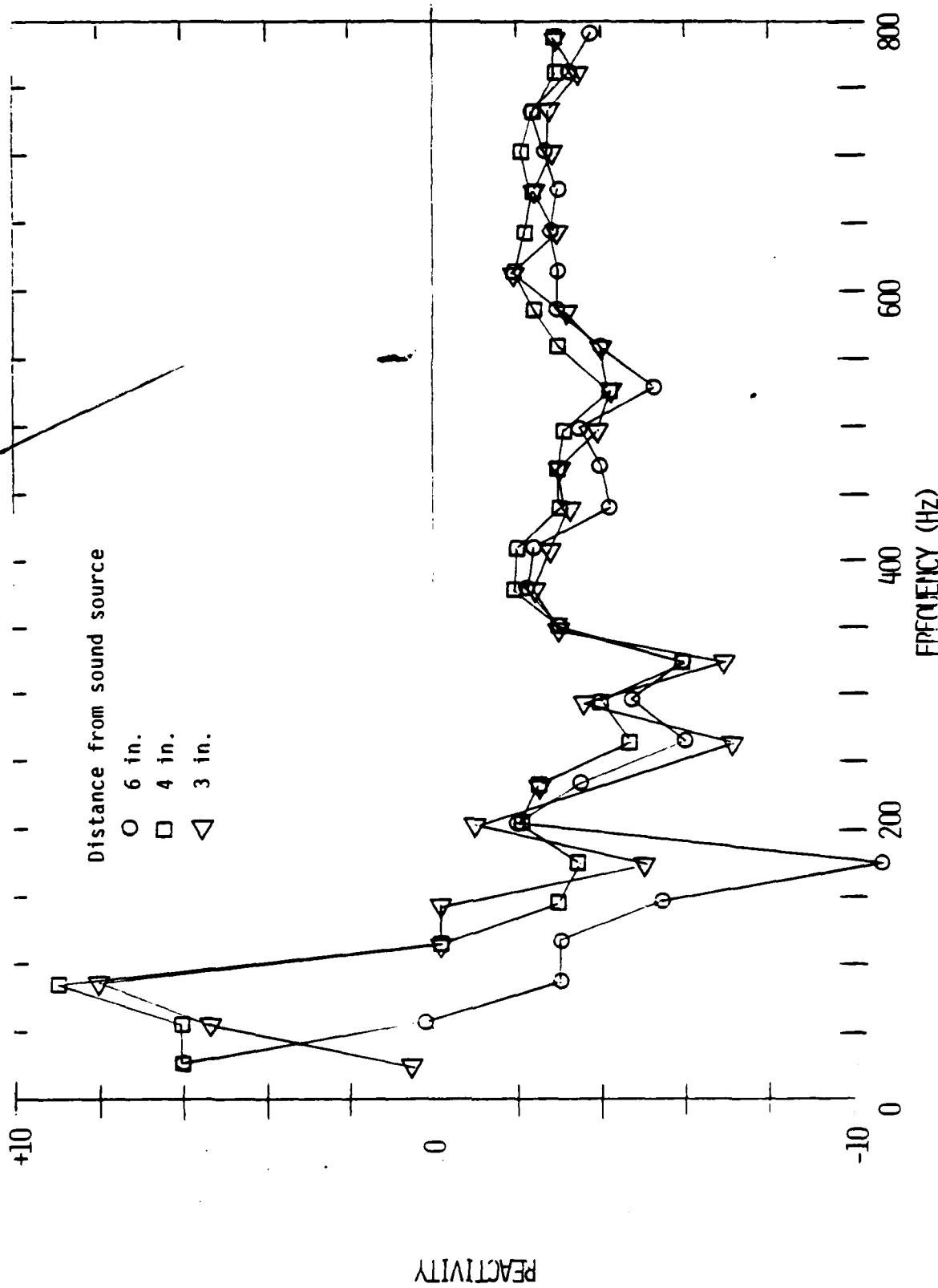
Fig. 17. Environmental reactivity in trailer with background noise (12-mm spacer).
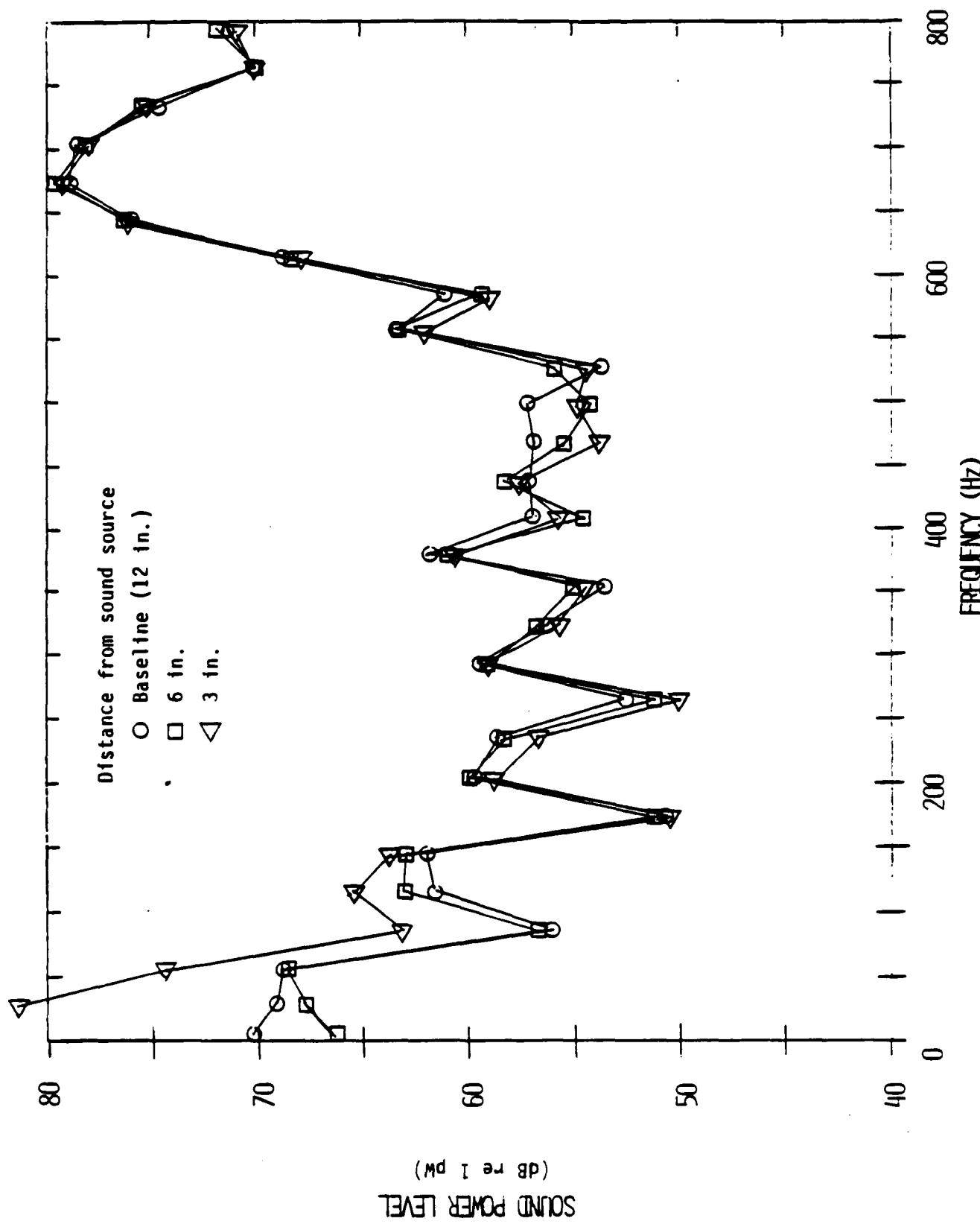
Fig. 18 Sound power measurement results in anechoic chamber (50-mm spacer).

34
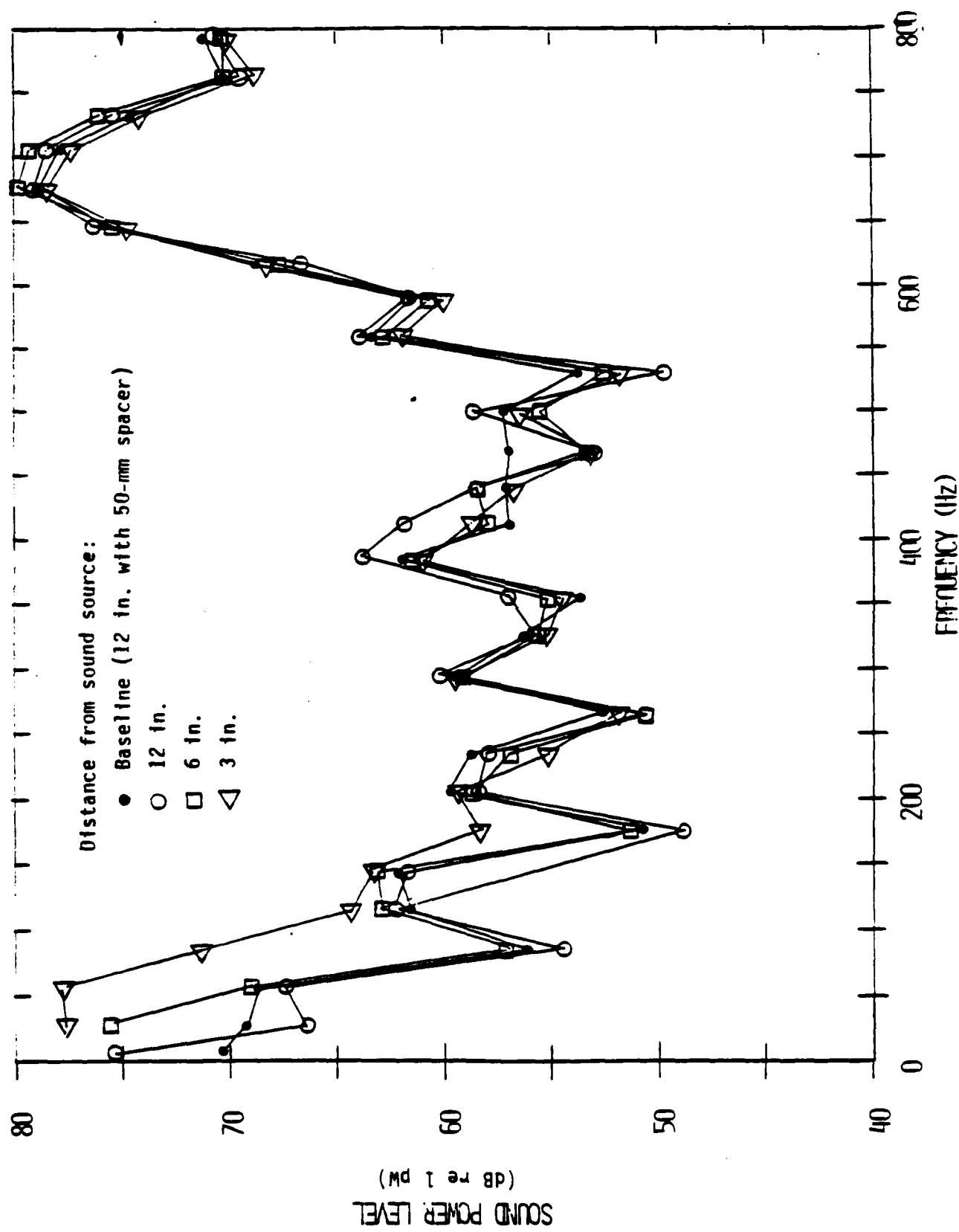
Fig. 19 Sound power measurement results in anechoic chamber (12-mm spacer).
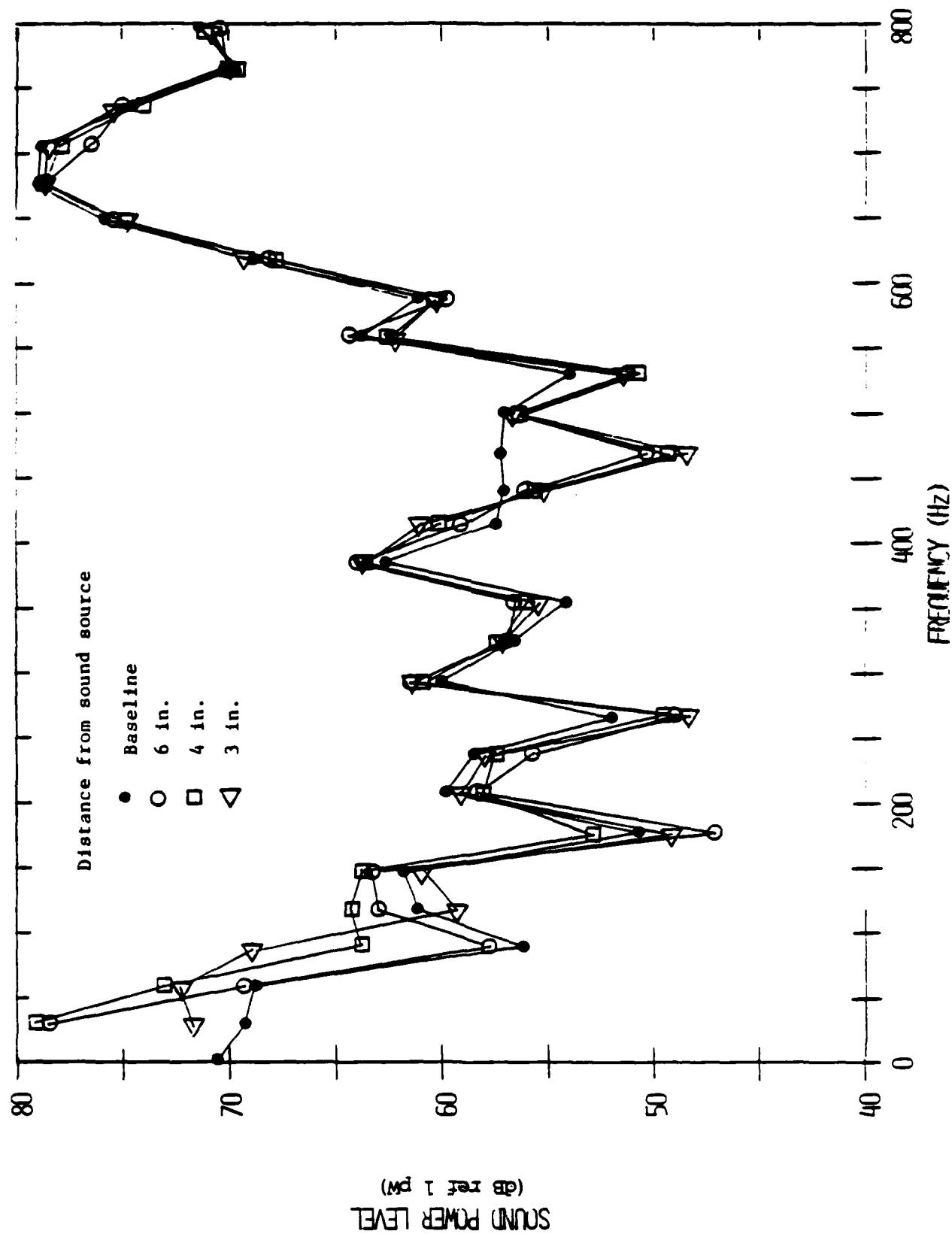
Fig. 20. Sound power measurement results in tool shed (50-mm spacer)

FREQUENCY (Hz)

SOUND POWER LEVEL
(dB ref 1 pW)

Distance from sound source

●	Baseline
O	6 in.
□	4 in.
▽	3 in.

36
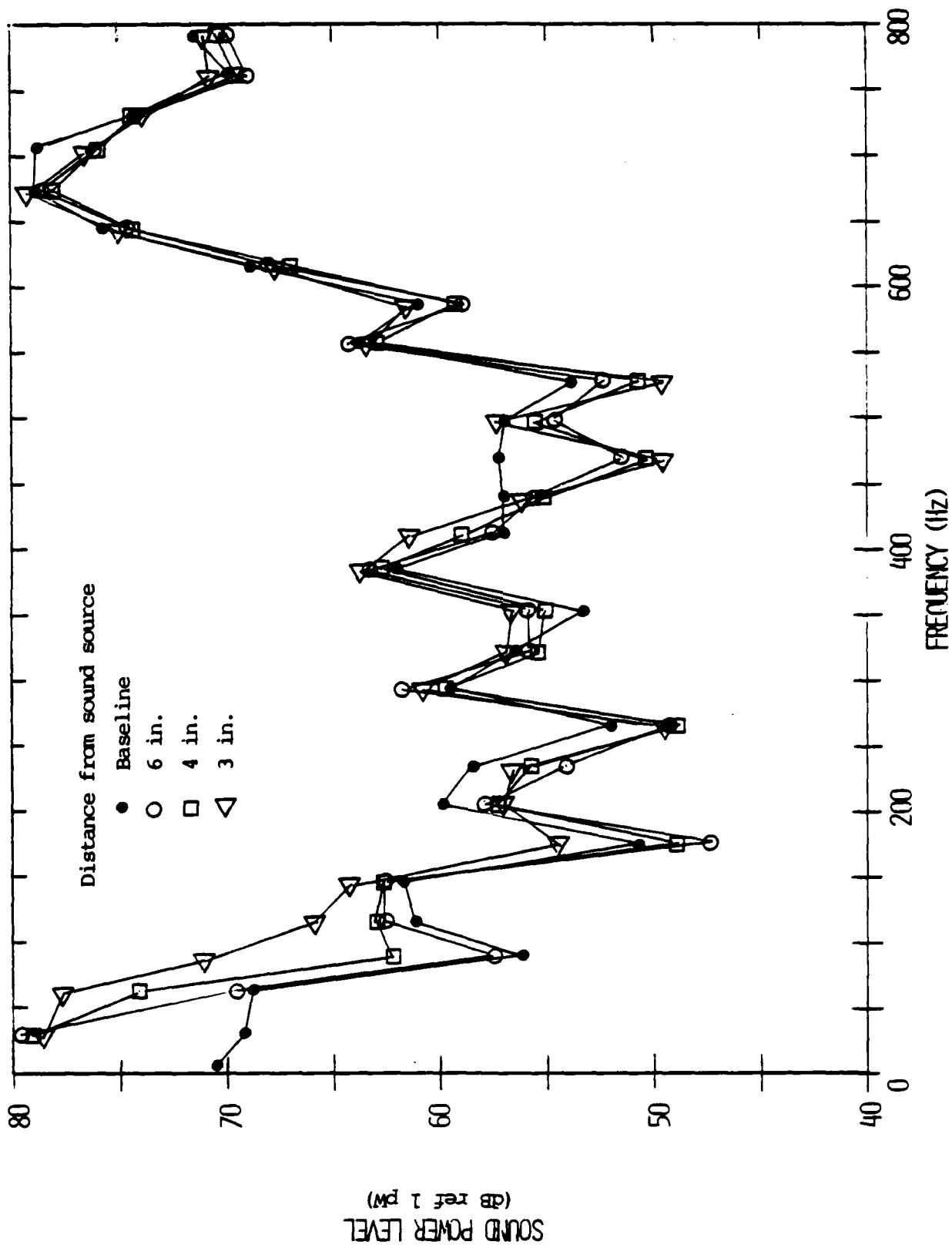
Fig. 21. Sound power measurement results in tool shed (12-mm spacer).
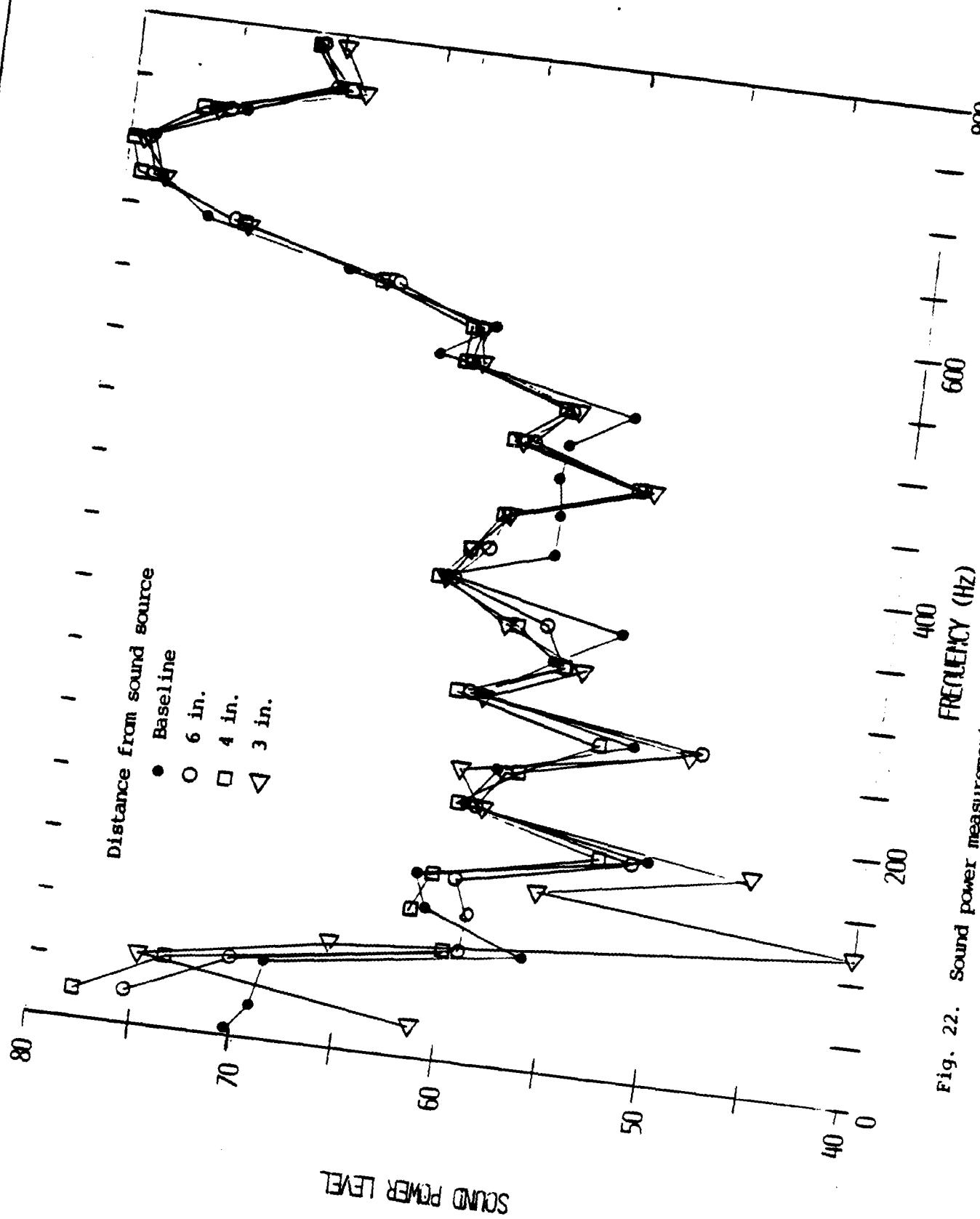
Fig. 22. Sound power measurement results in trailer with background noise (50-mm spacer).

SOUND POWER LEVEL

FREQUENCY (Hz)

Distance from sound source

● Baseline
○ 6 in.
□ 4 in.
▽ 3 in.

38
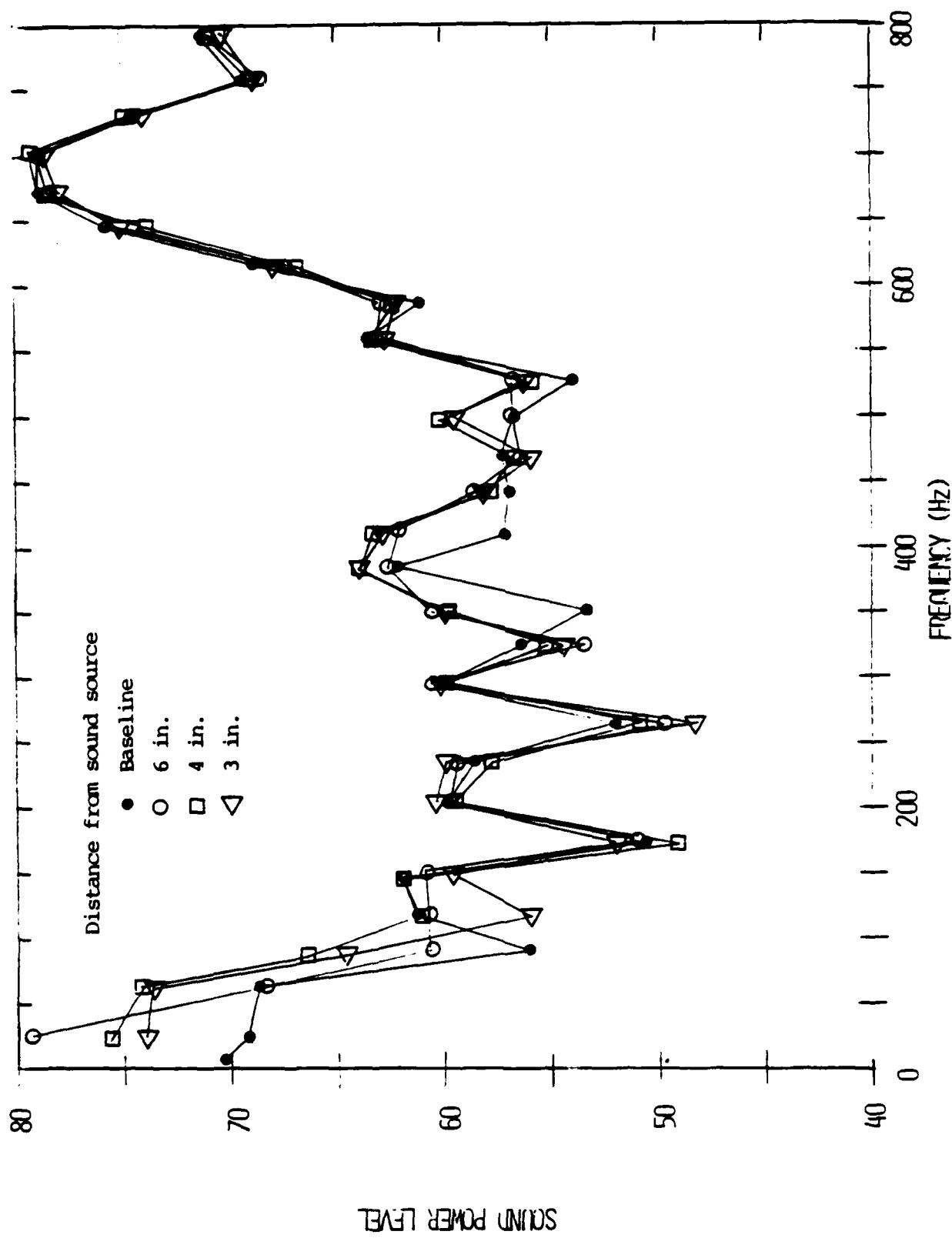
Fig. 23. Sound power measurement results in trailer with background noise (12-mm spacer).

Table 4. Low frequency limits for sound power
measurements in experiment 2. The phase
mismatch error in the system was 0.2°.

| Environment	Spacer* (mm)	Distance (in.)	Low Frequency Limit (Hz) ($\pm$ 2 dB) †		
			Experimental	Predicted from Reactivity checks	
				50-mm spacer	12-mm spacer
Anechoic Room	50	12	15	20**	
		6	30	30	
		3	150	180	
	12	12	60	60	
		6	60	60	
		3	150	180	
Tool Shed	50	6	60	120††	120††
		4	150	120††	120††
		3	150	150††	150††
	12	6	60	120††	120††
		4	120	150††	150††
		3	150	210	150††
Trailer w/background noise	50	6	60	60 ††	60 ††
		4	120	120	120††
		3	180	120††	150††
	12	6	120	120	210
		4	120	120	150
		3	150	120††	150††

* Spacer length between the two microphone faces in the sound intensity probe. This
   is the same as the microphone spacing referred to earlier.
† 2 dB was used due to variability in pump.
# Microphone spacing in reactivity check (intensity part).
** Predicted from Table 1.
†† Predicted limit at failure of reactivity check — this is where the reactivity
   becomes positive and does not make sense.

The results from these tests had to be interpreted carefully since the vacuum/pressure

pump was not exactly steady. Enough of the desired frequencies (the

piston induced fundamental and its harmonics) were steady enough, however, (within 2 dB) to draw a conclusion.

In the nonanechoic environments for the 3 in. and 4 in. and sometimes for the 6 in. distances, and for the 3 in. distance in the anechoic environment, little or no improvement was seen for the experimental low frequency limit with the use of the 50-mm spacer. The use of the 12-mm spacer, at times, produced a lower frequency limit. This indicates the presence of error due to the varying intensity near field effect. Table 3 showed that wider transducer spacings are more prone to this phenomena. It appears that the near field effect will worsen in bad acoustic environments.

Checking reactivity with equipment that measures smaller phase angles than the sound intensity measurement equipment seemed desirable. Such a reactivity check was done by attempting to use a 50-mm spacer in the intensity probe for the intensity part at first. This should predict the low frequency limits for use of the 12-mm spacer for the sound power measurements. The equipment being used was phase matched quite well, 0.2° or better up to 1000 Hz, and no phase matching technique was available that would better it. The modified switching phase matching technique did not improve the equipment phase match. The plane wave technique was not used due to insufficient equipment. The results of the reactivity checks and their relation to the experimental sound power low frequency limits are summarized below.

The reactivity checks with the 50-mm spacer often failed at or above the experimental low frequency limits for the sound powers with the 12-mm spacer. For the 50-mm spacer, this failure was apparently caused by near field effects at low frequencies, since the 12-mm spacer reactivities gave the same or lower low frequency limits. The failure in the 12-mm reactivity checks was likely due to phase mismatch. The 12-mm spacer reactivities failed at about the experimental sound power low frequency limits for that spacer. This was expected since the same equipment was used for the reactivity check

41

and the sound power measurement. The reactivities with the 50-mm spacer predicted (within 30 Hz) the sound power measurement low frequency limit with the 12-mm spacer only for the 6 and 4 in. microphone distances in the trailer and the anechoic chamber. For the other measurements using the 12-mm spacer in the tool shed and trailer, the measurement limits were best predicted when using the same spacer for the reactivity check and the sound power measurement. The experimental low frequency limits for the 50-mm spacer measurements were best predicted using the 50-mm spacer for the reactivity check. Space and equipment limitations did not allow the use of a larger spacer. The low frequency results for the 50-mm reactivity check were better in the trailer than in the tool shed. This indicates that the near field effect was worse in the tool shed. Also it appeared that near field effects are more of a low frequency problem, when measurement is done only a small portion of wavelength away from the source.

When using the same equipment for the reactivity check as for the intensity/sound power measurements, the only way to determine the limiting frequency ranges is to assume that when the reactivity check makes no sense, the intensity/sound power measurements will also be bad. Rechecking the reactivity check with the transducer positions switched may prevent false conclusions, but the switching technique can be misleading with equipment that is phase matched to one or two tenths of a degree. For our experiments, the intensity probe could not be properly inverted due to space limitations.

It was noted on the reactivity plots for the trailer measurements (Figs. 24 and 25) that the reactivity for the 6 inch distance was often greater than for the other distances. This indicates that it may be desirable to measure close to the sound source when background noise levels are high.

The low frequency limits were predicted assuming a phase mismatch of 0.2°. The analyzer, power supplies and the tape recorder were checked and found to contribute

42

approximately an additional 0.1° phase error to the 0.1° phase error documented for the intensity probe.

The sound power readings in the trailer were not affected by the background noise to any large degree. An inconsistancy was seen around 350 to 450 Hz. The reactivity here was not large, indicating that pump instability may have caused the problem. The environmental reactivity was affected by the background noise, as shown by increasing values in Figs. 16 and 17 for the 6 in. distance, but not enough to grossly affect the sound power measurements. This increased reactivity may explain the high predicted low frequency limit for the 6 in. distance using the 12 mm spacer listed in Table 4. Thus a fair amount of background noise again failed to affect the sound power measurement to any large degree.

For measurements quite close to the sound source, the following rules can be applied:

1. To avoid near field effects, it seems best to measure a distance from the sound source's surface of at least 3 times the probe's transducer spacing, especially in reactive environments. Near field errors become evident beginning with measurements at a 6 in. distance using the 50-mm (about 2-in.) transducer spacing.

2. Pick a suitable measurement surface. A hemispherical or a conformal surface may be preferrable; they may reduce environmental reactivity because the intensity probe remains pointed toward the source throughout the measurement routine. Divide the surface into enough subareas to provide sufficient sound field resolution.

3. Measure the average sound pressure and sound intensity levels over the entire measurement surface to find the reactivity as in Appendix B. If possible, use equipment that is less prone to phase mismatch error then the equipment to be used for the measurement (for example, a larger microphone spacing or a phase calibration). The plane wave phase calibration may be more accurate due to better controlled conditions. Find the reactivity and use nomogram in Fig. A.1. of Appendix A with a known or assumed equipment

43

phase mismatch to find the valid frequencies of measurement. If it is suspected that near field effects exist, recheck the intensity part of the reactivity measurement using a smaller transducer spacing. If the reactivity check fails at a lower frequency, then near field effects existed for the original microphone spacing. If the same equipment must be used for the sound power measurement and for the reactivity check, the sound power measurement frequency limits will probably be determined from the failure points of the reactivity check (when the reactivity is positive or very large negative). If the frequency range found for measurement is not desirable, use a different microphone spacing or distance to the source to reduce the effects of phase mismatch and/or near field effects. Watch out for near field effects and finite difference error when using a larger transducer spacing. If the measurement distance to the source is changed, recheck the reactivity.

4. If desired, double check by moving the probe in and away from the source while checking the validity of the sound intensity measurements on the analyzer or computer CRT. Do this for a number of points around the source.

CONCLUSIONS

The cross spectrum function was used in taking sound intensity measurements. This allows the application of phase calibrations to reduce the effect of instrumentation phase mismatch. Also, standard dual channel FFT spectrum analyzers can be used for sound intensity measurements. A method of using two pressure sensing transducers spaced a finite distance apart was developed for sound intensity use.

For sound power determination, it appears that the sound intensity method is just as accurate as the ISO 3744-1981 (E) method, which measures sound pressure in an anechoic environment, for frequencies at which phase matching errors or near field errors do not arise. Sound intensity measurements can be used to find the sound power output of sound sources in less than ideal environments. However, the intensity method should not be used when the environmental reactivity is too large. The valid, phase error-free frequency range

44

can be found by finding the reactivity over the measurement surface and using Table A.1 in Appendix A to estimate the true phase difference. By knowing the measurement system phase mismatch, or the accuracy of the phase calibration, one can visualize the effects of phase mismatch-induced error. In our experiments, problems in taking reactivity measurements occurred very close to the sound source due to near field effects. Often the same equipment must be used for both the reactivity check and the actual measurement. In this case, one must be careful in interpreting the results. To avoid near field effects or intensity variations between the two transducers, stay at least three times the microphone spacing from the sound source surface when measuring frequencies near the lower limit allowable for equipment phase mismatch.

The sound intensity method is useful for onsite and laboratory sound power determinations when an anechoic chamber is not available. For highly directional sources, the intensity method is more accurate then the ISO 3744-1981 (E) method at high frequencies. At very low frequencies, regardless of the source, the ISO 3744-1981 (E) method will be more reliable, when the proper anechoic space is available.

When using the sound intensity method for finding sound power, some care is required to find the measurement limitations due to the measuring equipment and the environment. Within these limitations, however, the method is accurate and reliable, even in nonanechoic environments.

45

APPENDIX A

REACTIVE SOUND FIELDS

Active sound energy propogates away from its source. The sound pressure and the particle velocity are in phase with each other. Reactive sound does not propagate and the pressure and velocity are $180°$ out of phase. Sound intensity instrumentation will measure only active sound since the time averaged product of the sound pressure and particle velocity is zero when the phase between them is $180°$. The presence of reactive sound energy will affect the measurement phase difference* when active sound intensity is measured. The reason is shown in equations below (Gade et al [5]).

$$I_m = I_t + I_{er} \quad \text{watts/meter}^2, \tag{A.1}$$

where

I_m=measured sound intensity (watts/meter^2),

I_t=true sound intensity (watts/meter^2), and

I_{er}=sound intensity error (watts/meter^2).

I_{er} can be given by

$$I_{er} = \frac{I_{re} p_t}{p_{re}} \quad \text{watts/meter}^2,$$

where

p_t=true sound pressure (pascals),

p_{re}=reactive sound pressure (pascals), and

I_{re}=reactive sound intensity (watts/meter^2).

I_{re} is given by

$$I_{re} = \frac{\phi_{re} p_{re}^2}{r f \rho 360°} \quad \text{watts/meter}^2, \tag{A.2}$$

* This phase difference is the sound field phase difference between the two transducers in the intensity probe, not between the sound pressure and the particle velocity.

46

where

ϕ_{re}=phase error (mismatch in equipment) (degrees),

f=frequency (Hz),

ρ =fluid density (kg/meter^3), and

r=transducer spacing (meters).

The result will be

$$I_m = I_t + \frac{\phi_{re} P_{re}^2 P_t}{r f \rho 360} \quad \text{watts/meter}^2. \tag{A.3}$$

The sound power measured by the equipment will be composed of the true (actual) sound power plus a sound power error factor composed of the phase mismatch and its effect with respect to the measurement environment reactivity. This relation to the reactivity is given by,

$$W_m = W_t + W_{er} \qquad \text{watts,} \tag{A.4}$$

where

W_m=measured sound power (watts),

W_t=true sound power (watts), and

W_{er}=sound power error (watts).

Since sound power equals intensity X area, the error in the sound power measurement can be given as follows:

$$W_{er} = \sum_{i=1}^{n} A_i \frac{I_{re} P_{t,i}^2}{P_{re}^2} = \frac{I_{re}}{P_{re}^2} \sum_{i=1}^{n} A_i P_{t,i}^2 \quad \text{watts} \tag{A.5}$$

where

n = the number of subareas in the measurement surface

47

The measured sound power is given by:

$$W_m = \sum_{i=1}^{n} A_i I_{m,i} \quad \text{watts.} \qquad (A.6)$$

W_t over W_m can be written as:

$$\frac{W_t}{W_m} = \frac{W_m - W_{er}}{W_m} = 1 - \frac{W_{er}}{W_m} = 1 - \frac{I_{re} \sum_{i=1}^{n} A_i P_{t,i}^2}{P_{re}^2 \sum_{i=1}^{n} A_i I_{m,i}} . \qquad (A.7) .$$

From the Eq. A.7 it can be seen that the overall reactivity over the entire measurement surface is needed for sound power measurements. Reactivity is calculated by taking the average sound pressure levels and sound intensity levels over the measurement surface. The pressure level is subtracted from the intensity level to gain the reactivity in decibels, as shown below.

$$\text{Reactivity (dB)} = L_I - L_p \qquad (A.8)$$

where

L_I=sound intensity level, dB re I_{ref},

L_p=sound pressure level, dB re P_{ref}.

By using the nomogram in Fig. A.1 (from Gade et al.[5]), one can estimate the actual phase difference to be measured for each frequency. Knowing the equipment phase mismatch or the accuracy of the phase calibration allows the valid frequency range of measurement to be determined.

To use the nomogram, locate the reactivity level for the desired transducer spacing and the desired frequency. Use the sloping lines to find the actual phase difference to be measured. The phase mismatch should not be more than one fifth of the actual phase angle for ± 1 dB error. The following formula estimates the error in dB for intensity due to phase mismatch.

$$L_I(\text{error due to phase mismatch}) = 10 \log_{10}\left(1 + \frac{\phi_{er}}{\theta_t}\right) dB,$$

48

where

L_I=sound intensity level,

ϕ_{er}=phase error(mismatch),

Θ_t=true phase difference between transducers.
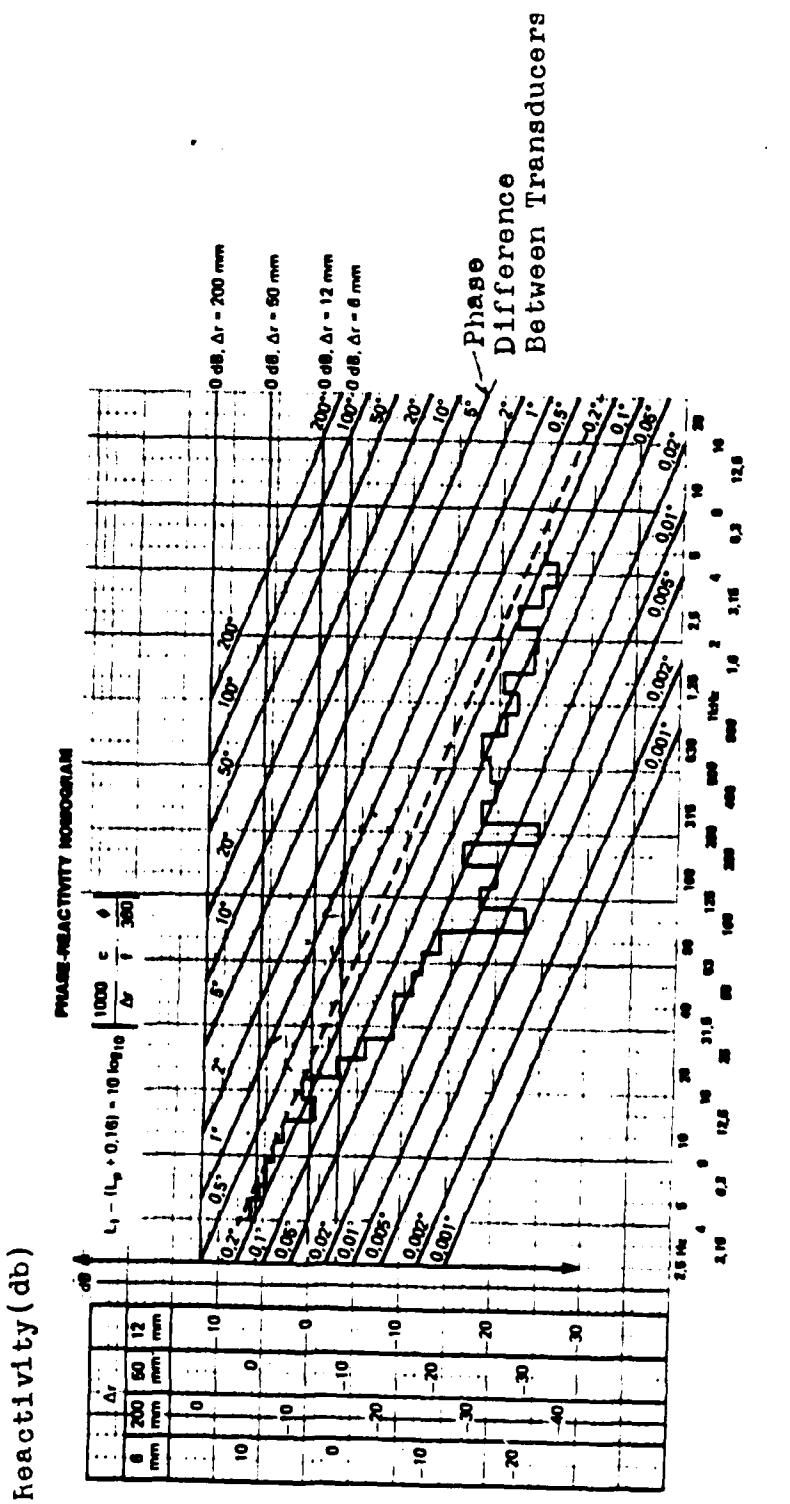
Fig. A.1. Phase-reactivity nomogram for determining the effect of enviromental reactivity on sound intensity measurements.

Δr = microphone spacing

APPENDIX B

CALIBRATION METHODS FOR MAGNITUDE AND PHASE

Three phase calibration methods will be discussed in this appendix, two switching techniques and a plane wave technique. The concept of measurement phase mismatch error will be introduced. The phase difference measured between the two transducers, consisting of the actual phase difference plus any phase mismatch error, can be expressed as[5].

$$\theta_m = \theta_t + \phi, \tag{B.1}$$

where,

θ_m = measured phase difference,

θ_t = true phase difference,

ϕ = system phase mismatch for measuring equipment.

The first phase calibration method discussed here can be called the "standard switching[2] technique." For this method, Eq. B.1 is used to express the measured phase difference, and then transducer positions are switched. The measured phase difference will be:

$$\theta_m = -0 + \phi \tag{B.2}$$

Equations B.1 and B.2 can be subtracted to yield the actual phase difference if the switching is done during the actual measurement:

$$\frac{(\theta_t + \phi) - (-\theta_t + \phi)}{2} = \theta_t \tag{B.3}$$

The advantage of using standard switching technique is that absolutely drift-free equipment is not needed. The disadvantage is that it must be done for each measurement, and for multiple intensity measurements it is cumbersome. For sweeping type measurements, as for sound power determination, it may not be accurate.

51

The second phase calibration method can be referred to as a modified switching[2] technique. Equations B.1 and B.2 can be added to find the phase mismatch. This result can then be stored for later use in the actual measurements. See Eq. B.4 below.

$$\frac{(\theta_+ + \emptyset) + (-\theta_+ + \emptyset)}{2} = \emptyset \qquad (B.4)$$

The advantage of the modified switching technique is that the phase match is stored for easy application in actual intensity measurements. The disadvantage is that the equipment being calibrated must not drift with its phase response.

For the standard switching technique the complex cross spectra found for the normal and switched transducer positions can also be multiplied, then the square root taken as below to find the true measurement cross spectrum (Chung[6]):

$$G_{12(true)} = \sqrt{G_{12}{}^n \, G_{12}{}^{*,s}} \quad , \qquad (B.5)$$

where

    G_{12}=cross spectrum between channels 1 and 2 (complex),

    n=normal transducer position,

    s=switched transducer position,

    *=complex conjugate.

The complex cross spectrum can be divided, then square rooted to find a calibration factor to be stored for use with later intensity measurements in the modified switching technique (Stunsnick[2]):

$$H_{12}' = \sqrt{\frac{G_{12}{}^n}{G_{12}^{s,*}}} \quad , \qquad (B.6)$$

where

H_{12}'=phase correction factor.

This leads to the following equation,

$$G_{12(true)} = \frac{G_{12(measured)} \cdot}{H_{12}'} \qquad\qquad (B.7)$$

The third phase calibration method is a plane wave technique. Subjecting both transducers to the same signal also will yield the phase mismatch. This is done by placing the transducers in a completely diffuse sound field in a cavity calibrator, or by subjecting them to plane waves as in a plane wave tube. See Figs. B.1 and B.2.

The found phase difference is then stored for later intensity measurements. The advantages and the disadvantages are the same as for the modified switching method. An additional advantage may be that this technique is more accurate, both because conditions are better controlled and because only one measurement is needed during the calibration. Instead of finding the phase mismatch, the plane wave technique can be used to find the transfer function between the transducer channels. The cross spectrum result is then divided by this transfer function as below.[2]

$$G_{12(true)} = \frac{G_{12(measured)}'}{H_{12}} \qquad\qquad (B.8)$$

where

H_{12}=transfer function between channel 1 and 2.

With this method, the transducers are matched in phase and magnitude to the transducer in channel A. A magnitude calibration needs to be done only on the transducer in channel A.

For the switching phase calibration techniques, a magnitude calibration must be done on both microphones in the sound intensity probe. This calibration is done using standard microphone calibrators. The sensitivity for each microphone is found and inputted into the FFT analyzer during analyzer setup. A few FFT

53

analyzers do not allow input of transducer sensitivities. The older Nicolet
dual channel FFT analyzers are examples. For these analyzers, a magnitude
calibration factor is found using the auto spectrum function. The magnitude
calibration factor is then intergrated into the process of finding the true
cross spectrum function. Refer to reference 2 (Stusnick) for more on auto
spectrum magnitude calibration factors.
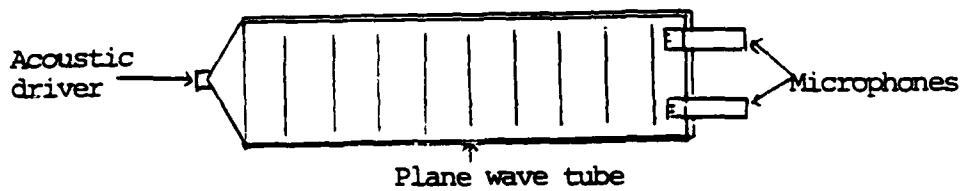
Fig. B.1. Plane wave phase calibrator
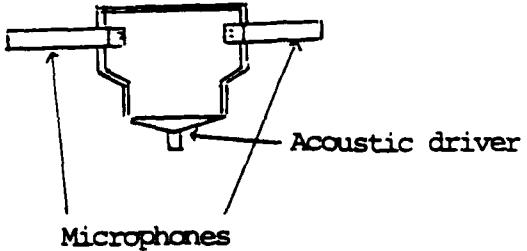
Fig. B.2. Cavity phase calibrator

APPENDIX C

REAL TIME SOUND INTENSITY DETERMINATION

Real time analyzers directly compute sound intensity, using the two microphone method. The cross spectrum is not used. The instantanous sound pressure is multiplied by the instantanous particle velocity indirectly. One measurement system available uses one pressure transducer with a velocity transducer to compute $I=\overline{pu}$ directly. The equation used by real time analyzers with the two pressure transducers is:

$$I = \overline{pu} = \frac{1}{2\rho r} \int \overline{(p_1 + p_2) \ (p_2 - p_1)dt} \ , \tag{C.1}$$

where

p_1=pressure of transducer 1,

p_2=pressure at transducer 2,

dt=time differential, and

$\overline{}$ =time averaged

This speeds up the measurement. The main disadvantage is that phase calibrations cannot be applied since the cross spectrum is not found. Also real time equipment usually measures in 1/3 octave or octave bands only. Unlike FFTs, these analyzers usually are limited to pressure, intensity, and motion (acceleration) measurements.

APPENDIX D

DESCRIPTION OF COMPUTER PROGRAMS

A computer program to run the B&K 2032 analyzer with a Hewlett Packard (HP) 217 computer was developed for the sound power measurements using the intensity method. A program to run the General Radio 2512A analyzer with an HP model 85 computer was used for the sound pressure method. The intensity program takes the averaged intensity data from the BK 2032, which calculates intensity in the analyzer, in watts/meter^2 for each subarea in the sound power measurement surface. The program then multiplies the data by the subarea area in meters. The result for each subarea is added to the previous total to obtain the sound power. The program will convert the results to decibels and will plot on the computer screen and on external printers and plotters. The sound pressure program simply stores sound pressure measurements from each microphone and then averages all the microphones when done. The formula below is used to calculate the sound power from sound pressure measurements.

$$L_w = L_p + 20 \log_{10} \frac{r}{r_{ref}} - 0.16,$$

where

$r_{ref} = .282$ meter,

L_w = sound power level (db ref 1pW),

L_p = sound pressure level (db ref 20 uPa), and

r = radius of measurement hemisphere (ISO 3744-1981 (E), Fig. 2).

This program also converts to decibels and plots the data.
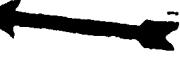
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